ASHRAE® GUIDELINE

Measurement of Energy and Demand Savings

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ASHRAE Guideline 14-2002, Measurement of Energy and Demand Savings

(This foreword is not part of this guideline but is included for information purposes only.)

FOREWORD

Guideline 14 was developed by ASHRAE to fill a need for a standardized set of energy (and demand) savings calculation procedures. The intent is to provide guidance on minimum acceptable levels of performance for determining energy and demand savings, using measurements, in commercial transactions. Note that it is entirely possible to have a sale/purchase, lease, or other arrangement for energy-efficient equipment that does not involve measurements. Indeed, the vast majority of transactions are of this type. However, if the savings determination is to be based on measurements, certain minimum requirements are necessary in order to avoid a process that appears to be based on actual savings but might be highly inaccurate, biased, or random.

It is expected that ASHRAE Guideline 14 will be used for transactions between energy service companies (ESCOs) and their customers and between ESCOs and utilities, where the utilities have elected to purchase energy savings. Use of ASHRAE Guideline 14 is expected to provide savings results sufficiently well specified and reasonably accurate so that the parties to the transaction can have adequate assurance for the payment basis. Other applications of ASHRAE Guideline 14 may include documenting energy savings for various credit programs, e.g., emission reduction credits associated with energy efficiency activities.

Determining savings with measurements in accordance with this guideline involves measuring post-retrofit energy use and comparing that to the measured pre-retrofit use, adjusted or normalized, to act as a proxy for the conditions that would have prevailed had the retrofit not been performed. Therefore, determining energy savings through the use of measurements involves more than just verifying that new equipment has been installed and can function as expected, although those tasks are usually a necessary part of determining savings. In addition, energy savings cannot be claimed to be "measured" if no pre-retrofit data are available.

Sampling is often used in projects involving end-use monitoring or what we call the "retrofit isolation approach." Annex B gives procedures to calculate the added uncertainty due to sampling. ASHRAE Guideline 14 may be used to measure the energy savings from a utility sponsored or contracted multiple-building energy conservation project. Applying ASHRAE Guideline 14 to such a project would allow the use of Annex B to calculate the measurement uncertainty directly. The net impacts of large-scale utility energy conservation programs, such as those that may involve market transformation or standard offers for purchase of conservation energy, are specifically excluded from the scope of ASHRAE Guideline 14, although individual and multiple-building projects within such programs are covered.

ASHRAE Guideline 14 primarily addresses measurements of energy and demand for determining savings. Other tasks are needed in any energy performance contract. These can include determining appropriate utility rates, inspecting and commissioning equipment, etc. Users of ASHRAE Guideline 14 who are interested in learning more about some of the contractual issues and types of performance contracts will find relevant discussion in the DOE publication "International Performance Measurement and Verification Protocol" (IPMVP 2000) available at <www.ipmvp.org>.

1. PURPOSE

The purpose of this document is to provide guidelines for reliably measuring the energy and demand savings due to building energy management projects.

2. SCOPE

2.1 This guideline provides for using measured pre-retrofit and post-retrofit data to quantify the billing determinants (e.g., kWh, kW, MCF, etc.) used for calculation of energy and demand savings payments to energy service companies, utilities, or others.

2.2 ASHRAE Guideline 14 includes the determination of energy and demand savings from individual facilities or meters.

2.3 Procedures include all forms of energy, including electricity, gas, oil, district heating/cooling, etc.

2.4 The procedures encompass residential, commercial, and industrial buildings.

2.5 The procedures do not include

a. sampling methodologies that may be used in large-scale demand-side management programs,
b. metering standards, or
c. major industrial process loads.

3. UTILIZATION

3.1 Basic Methodology

There is no direct way of measuring energy use or demand savings since instruments cannot measure the absence of energy use or demand. However, the absence of energy use or demand can be calculated by comparing measurements of energy use and/or demand from before and after implementation of an energy conservation measure (ECM). Simple comparison by subtraction of post-retrofit energy use from the pre-retrofit quantity does not differentiate between the energy impacts of the ECM and those of other factors such as weather or occupancy. In order to assess the effectiveness of the ECM alone, the influence of these other complicating factors, such as weather and usage factors, must be removed.

This guideline addresses determination of energy savings by comparing before and after energy use and making adjustments for non-ECM changes that affect energy use. The basic method of this guideline is shown in Figure 3-1. It involves projecting energy use or demand patterns of the pre-retrofit (baseline) period into the post-retrofit period. Such projection requires adjustment of baseline energy use or demand to different conditions of weather, occupancy, or other energy-governing variables. Savings are then determined as:

Savings = (Baseline energy use or demand projected to Post-retrofit conditions) minus (Post-retrofit energy use or demand)

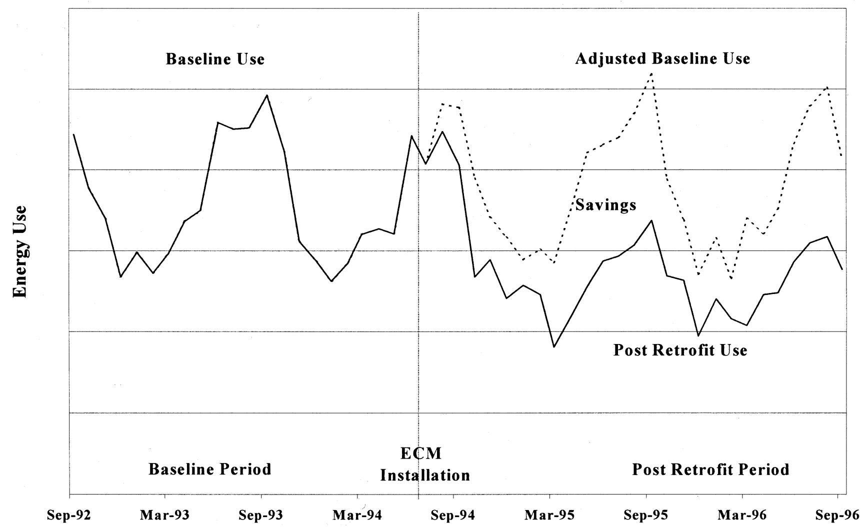

Figure 3-1 Determining savings.

In this common form, the derived savings can also be considered as avoided energy use or demand, since if the retrofit had not taken place, the post-retrofit period energy use or demand would have been that much higher.

3.2 Range of Approaches

This guideline presents three basic approaches for determining savings and advises on appropriate application of each. No one way can be used in all situations. The three basic approaches described here must be tailored to suit each project's budget and its need for certainty and timeliness. This guideline defines terms to help reduce uncertainty and control the costs of assessing an ECM's performance. However, this document may also be used for other purposes, such as establishing an energy use monitoring system or assessing the opportunities for improving energy use.

Clause 5 provides both an overview and compliance terms for each of three basic approaches to savings measurement. Clause 6 provides background and definition on each of the approaches. Clause 7 and Annex A present recommendations on measuring equipment and systems. Annex B presents methods of calculating uncertainty in savings measurements. Annex C provides specific examples of savings measurement processes that are compliant with this guideline. Annex D discusses regression analysis techniques. Annex E is a normative annex detailing various retrofit isolation approach techniques.

3.3 Uncertainty and Cost

Measurements of energy savings compare the actual energy use to an estimate of what energy use would have been in the absence of the ECM (See Figure 3-1). The estimate of what energy use would have been requires data analysis and assumptions about how factors affecting energy use have changed since the baseline period.

Weather and occupancy are examples of two factors that often change and often affect energy use or demand. Relationships must be found between energy use and such factors in order to remove the influence of the factors from the energy savings measurement. These relationships are usually determined through data analysis, not textbook formulae. Since data analysis can be conducted in an infinite number of ways, there can be no absolute certainty about the relationship chosen.

Factors that do not change often, such as building dimensions, usually do not require assumptions about how they affect energy use, even though they may have a significant impact on energy use. However, it must either be assumed that such fixed factors do not change, or a means must be established to verify that they remain constant throughout the monitoring period.

The need for certainty must be carefully balanced with measurement and analysis costs, recognizing that absolute certainty is not achievable. There are numerous sources of uncertainty, including instrumentation or measurement error, normalization or model error, sampling error, and errors of assumptions. Each of these sources of error can be minimized to varying degrees by using more sophisticated measurement equipment, analysis methods, sample sizes, and assumptions. However, it is also generally true that more certain savings determinations follow the law of diminishing returns, where further increases in certainty come at progressively greater expense.

The cost of measuring savings needs to be kept in perspective relative to the savings being earned. If only one measurement is to be done, more effort can be put into that measurement than if periodic measurement is needed. For example, where the same retrofit is performed on many similar energy-using systems within a facility, and investment evaluation is only needed once, adequate accuracy may be obtained by careful determination of savings in one system, then factoring up the result for all systems in the facility.

Some aspects of a savings determination do not lend themselves to quantitative uncertainty assessment. Aspects such as human error or incorrect placement of sensors can only be qualitatively assessed.

This document provides guidance on how to calculate the quantifiable uncertainties (see clause 5.2.11.4). For some situations it sets maximum acceptable savings uncertainties in order to claim compliance with this guideline. Because of the complexity and effort required to calculate savings uncertainty in some situations, this guideline defines a prescriptive path that does not require such assessment of uncertainty.

3.4 Planning and Objectives

Any savings determination process must begin with planning. This planning is best done at the time the retrofit itself is being designed to ensure that all relevant data are gathered during the baseline period and that post-retrofit period data requirements and analysis can be obtained within an acceptable budget. A proper measurement and verification (M&V) plan should consider the objectives for the savings determination.

When implementing a program of one or more ECMs, there are three possible basic objectives for the savings determination. One or more of these objectives may have to be met for any particular project. Each basic objective is discussed below.

3.4.1 Determining Payments Under an Energy Service Contract. In many energy service contracts, savings are used to establish the required payments. The parties to such contracts may not appreciate that energy savings cannot be measured as exactly as energy use.

A critical parameter affecting the form of savings determination for this purpose is the significance that any uncertainty in the savings has to the total payments. The contract for services defines the interest that each party has in the certainty of the payment. The prescriptive compliance path in this guideline may simplify the understanding of the savings quantity. However, the performance compliance paths, which require assessment of the level of certainty, may best satisfy the concerns of all parties in the contract.

For example, certainty may be less important where the contract for services dictates that savings are only paid until defined costs are recovered rather than for a fixed period of time.

3.4.2 Controlling Energy-Using Systems. Knowledge about the level of savings achieved in any given period of time can be used to control operation of the energy-using systems and improve overall performance. Such control would aim to ensure that use excesses do not occur.

A critical aspect of the savings measurement for this purpose is its timeliness. If the savings information is fed back to those in control of energy use significantly after the fact, significant savings may have already been lost. If the savings reports are prompt and frequent, uncertainty may be of lesser importance since subsequent reports may correct for errors.

For example, there is little value in discovering during a mild month that the heating system did not perform as planned during the preceding winter. At that point there is no chance of recovering savings lost at the end of the heating season. Though the problem may be avoided next winter, without the ability to actually inspect operations when they are going off target, it is often impossible to determine what corrective action is needed for next winter. Use of monthly utility bills as the source of raw data often causes such long delays in savings reports that they are of limited value for control.

3.4.3 Justifying Retrofit Investments. An owner or energy service company may need to justify that its investment in energy retrofits made good economic sense. Such justification may be needed regularly or only once, with varying degrees of certainty. A critical aspect of the savings measurement is that its cost not significantly detract from the return on investment itself.

3.5 Compliance

3.5.1 Compliance Overview. This guideline contains minimum compliance requirements to ensure a fair level of confidence in the savings determination results. Since there are several purposes for determining energy and demand savings, and various computational methods are available to determine savings, it is important to balance the accuracy of the approach employed against the costs of implementation. Therefore, this guideline sets forth three specific approaches and provides at least one compliance path for each. The approaches are (1) whole building metering, (2) retrofit isolation metering, and (3) whole building calibrated simulation.

The specific compliance requirements are described in clause 3.5.3. In addition to some basic requirements common to all approaches, four compliance paths are defined. Each approach has a "performance path" requiring the performance of uncertainty analysis for each reported result. For the whole building approach, there is also a "prescriptive path" prescribing conditions under which no uncertainty analysis is required.

3.5.2 Specifying the Use of This Guideline. To require compliance or use of this guideline in a specification, one of the four compliance paths shall be specified, including the subclause number from clause 5.3.2. For performance paths, the maximum allowable uncertainty shall be specified. For the retrofit isolation approach, an Annex E technique shall be specified.

An example of proper specification of the use of this guideline is as follows: "Savings determination shall comply with ASHRAE Guideline 14, Path 2, Whole Building Performance Path, with a maximum allowable uncertainty of 20% at a 90% level of confidence."

3.5.3 Minimum Requirements for Compliance with This Guideline. Compliance with this guideline is achieved by following the basic requirements and one of the four compliance paths of clause 5.3. Examples of compliant savings determination processes are listed in Annex C. The general methodology of all compliant approaches is summarized below and shown in Figure 3-2.

a. Prepare a measurement and verification plan, showing the compliance path, the metering and analysis procedures, and the expected cost of implementing the measurement and verification plan throughout the post-retrofit period.
b. Measure the energy use and/or demand before the retrofits are applied (baseline). Record factors and conditions that govern energy use and demand.
c. Measure the energy use and/or demand after the retrofits are applied (post-retrofit period). Record factors

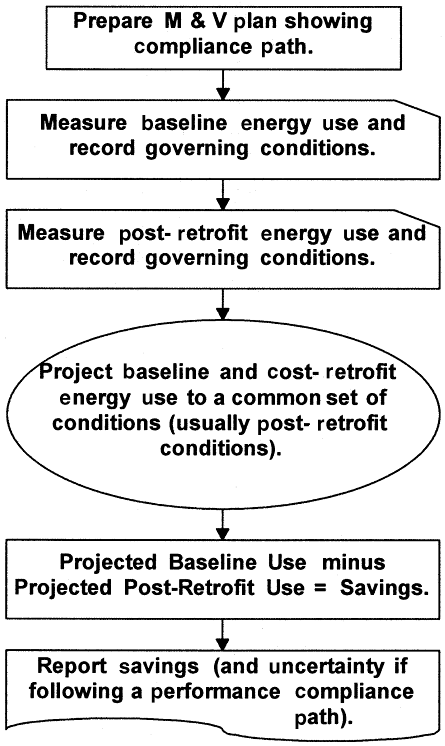

Figure 3-2 General approach.

and conditions that govern post-retrofit period use and demand.

d. Project the baseline and post-retrofit period energy use and demand measurements to a common set of conditions. These common conditions are normally those of the post-retrofit period, so only baseline period energy use and demand need to be projected.

e. Subtract the projected post-retrofit period use and/or demand from the projected baseline period use and/or demand to calculate the savings. Unless the whole building prescriptive path is followed, assess and report the level of uncertainty in the annual savings report.

For the three performance paths, the level of uncertainty shall not be greater than 50% of the annual reported savings (at the 68% confidence level).

4. DEFINITIONS

The following definitions represent how each term is used in ASHRAE Guideline 14 unless otherwise noted.

accuracy: an indication of how close some value is to the true value of the quantity in question. The term could also be used in reference to a model, or a set of measured data, or to describe a measuring instrument's capability.

algorithm for savings determination: the procedures to be followed for converting all relevant measured data and facts from the post-retrofit period to energy or demand savings using the baseline model.

baseline data: the measurements and facts describing facility operations and design during the baseline period. This will include energy use or demand and parameters of facility operation that govern energy use or demand.

baseline period: the period of time selected as representative of facility operations before retrofit.

billing data: information collected from invoices sent to an owner from the energy supplier, e.g., an electric or gas bill.

calibration: the process of comparing the output or results of a measurement or model with that of some standard, determining the deviation and relevant uncertainty and adjusting the measuring device or model accordingly.

chiller performance:

condenser load - the amount of heat added to the water removed from the load; the integrated product of the flow rate through the condenser and the temperature difference across the condenser.

COP - coefficient of performance, the ratio of net cooling capacity divided by energy input rate, expressed in consistent units.

evaporator load - the amount of heat removed from the water supplied to the load; the integrated product of the flow rate through the evaporator and the temperature difference across the evaporator.

tons - measure of cooling capacity equal to 12,000 Btu/h.

debug: to search for and eliminate malfunctioning elements or errors. For example, when used in reference to a computer simulation model, it means to fix incorrect user inputs, which may be due to errors such as mistyping a value, using an incorrect value, or modeling a system incorrectly.

demand: the time rate of energy flow. In the United States, demand usually refers to electric power and is measured in kW (equals kWh/h) but can also refer to natural gas, usually as therms or ccf per day. In many other countries, demand is commonly used with other energy sources, especially district heat.

metered demand - the average time rate of energy flow over a period of time.

coincident demand - the metered demand of a device, circuit, or building that occurs at the same time as the peak demand of the building or facility or at the same time as some other peak of interest, such as a utility's system load. This should properly be expressed so as to indicate the peak of interest, e.g., "demand coincident with the building peak."

peak demand - the maximum level of metered demand during a specified time period, such as a billing month, or during certain hours of certain days during the month, such as weekdays from 8 a.m. to 8 p.m.

billing demand - the demand used to calculate the demand charge cost. In the United States, this is very often the monthly peak demand of the customer, but it may have a floor of some percentage of the highest monthly peak of the previous several months (a demand "ratchet"). The billing demand in many countries may be the contract demand. Other variations and multiple billing demands are possible.

contract demand - the maximum demand, which may or may not be metered, that is expected or allowed under the contract with the utility providing the energy. This may be enforced by metering, circuit breaker (electricity), or orifice (district heat).

demand savings: the reduction in the demand from the pre-retrofit baseline to the post-retrofit demand, once independent variables (such as weather or occupancy) have been adjusted for. This term is usually applied to billing demand, to calculate cost savings, or to peak demand, for equipment sizing purposes.

digital data acquisition specification characteristics:

scan rate - an indication of how fast a recording instrument proceeds from measurement to measurement within a given scan.

scan interval - an indication of how often scans are initiated.

throughput rate - the maximum rate the entire data acquisition system can accept, process, and transfer data.

input range(s) - the range(s) of voltage signals the internal digital volt meter's analog to digital converter (A/D) can sense (direct current [dc], e.g., 0 to 10 Vdc, 0 to +/- 5 Vdc) with a maximum voltage limit (e.g., 200 Vdc) or alternating current (ac), e.g., 0 to 125 Vac rms).

energy: the capability of doing work. It takes a number of forms that may be transformed from one into another, such as thermal (heat), mechanical (work), electrical, and chemical. Customary measurement units are kilowatts (kWh), British thermal units (Btu), and quantity of steam or volume of hydrocarbon fuel.

energy conservation measure (ECM): installation of equipment, subsystems, or systems, or modification of equipment, subsystems, systems, or operations, for the purpose of reducing energy and/or demand (and, hence, energy and/or demand costs).

energy cost: the total cost for energy, including such charges as base charges, demand charges, customer charges, power factor charges, and miscellaneous charges.

energy savings: the reduction in use of energy from the pre-retrofit baseline to the post-retrofit energy use, once independent variables (such as weather or occupancy) have been adjusted for.

energy service company (ESCO): an organization that designs, procures, installs, and possibly maintains one or more energy conservation measures (ECMs) at an owner's facility or facilities.

error: deviation of measurements from the true value.

independent variables: the factors that affect the energy and demand used in a building but cannot be controlled (e.g., weather or occupancy).

main meter: the meter that measures the energy used for the whole facility. There is at least one meter for each energy source and possibly more than one per source for large facilities. Typically, utility meters are used, but dataloggers may also be used as long as they isolate the load for the facility being studied. When more than one meter per energy source exists for a facility, the main meter may be considered the accumulation of all the meters involved.

measure: use of an instrument to assess a physical quantity, or use of a computer simulation to estimate a physical quantity.

measured savings: savings or reductions in billing determinants, which are determined using engineering analysis in combination with measured data.

measurement system verification: that full range of checks and tests carried out to determine if all installed measurement system components, subsystems, systems, and interfaces between systems function in accordance with the measurement plan. Also used to ascertain the as-installed uncertainty of the measurement system.

meter: a device used to measure some quantity.

metered data: energy end-use data collected over time using a measuring device or group of measuring devices.

metering: collection of energy data using a measuring device or group of measuring devices.

model: a mathematical representation or calculation procedure that is used to predict the energy use and demand in a building or facility. Models may be based on equations that specifically represent the physical processes (refer to *simulation model*) or may be the result of statistical analysis of energy use data (refer to *regression model*).

baseline model - the set of arithmetic factors, equations, or data used to describe the relationship between energy use or demand and other baseline data. A model may also be a simulation process involving a specified simulation engine and set of input data.

regression model - a mathematical model based on statistical analysis of some measured data.

simulation model - a computer model that provides information on the energy-using systems in a building (e.g., HVAC, lighting, occupancy, plug loads, building envelope). The model serves as the input data for a specific computer building energy simulation program, along with weather data. When run, the computer simulation program will predict the energy use and demand in the described building for a time interval specified in the simulation model. Depending on the kind of simulation program and how it is set up to run, various kinds of output may be produced. (Refer also to *whole building calibrated simulation approach*.)

monitoring (equipment or system): gathering of relevant measurement data over time to evaluate equipment or system performance, e.g., chiller electric demand, inlet evaporator temperature and flow, outlet evaporator temperature, condenser inlet temperature, and ambient dry-bulb temperature and relative humidity or wet-bulb temperature, for use in developing a chiller performance map (e.g., kW/ton vs. cooling load and vs. condenser inlet temperature).

net determination bias test: the savings resulting from applying the baseline period's independent variable data to the algorithms for savings determination. The data so applied must reflect all exclusions or adjustments to actual measured data as documented for the baseline model.

normalization: adjustment of the results of a model due to changes in baseline assumptions (non-independent variables) during the test or post-retrofit period.

performance contracts: a binding agreement between two parties prescribing the range and magnitude of achievement required of equipment, subsystem, or system, which is provided by one party for the benefit and use of the other.

precision: the indication of the closeness of agreement among repeated measurements of the same physical quantity.

projected baseline: the baseline energy use or demand applied to the post-retrofit period and conditions.

pump performance:

capacity - volumetric flow rate delivered by the pump.

differential pressure - the difference in pressure between any two points in the system.

gage pressure - the measure of the total static and dynamic pressure exerted by a liquid, not including atmospheric pressure, per unit area.

operating load point - actual system operating capacity at the time an instrument reading is taken.

static discharge head - the static pressure of a fluid at the outlet of the pumping device, expressed in terms of the height of a column of the fluid, or of some manometric fluid, that it would support.

static pressure - the pressure exerted by a fluid at rest. In a dynamic system, static pressure is the difference between total and velocity pressures.

system effect - condition in the distribution system that affects pump performance and related testing procedures.

total pressure (head) - in fluid flow, the sum of the static pressure (head) and the velocity pressure (head).

velocity head - in a moving liquid, the height of the fluid, or of some manometric fluid, equivalent to its velocity pressure.

velocity pressure - the pressure that exists due to the velocity and the density of the fluid; i.e., it is a measure of the kinetic energy that exists in a fluid system.

post-retrofit period: the time following a retrofit during which savings are to be determined.

resolution: the smallest indicated increment in the value of a measured quantity that can be measured and reported by a recording instrument.

retrofit: energy conservation measure or measures installed and /or implemented as a single project at a specific time.

retrofit isolation: the savings measurement approach defined in ASHRAE Guideline 14 that determines energy or demand savings through the use of meters to isolate the energy flows for the system(s) under consideration.

savings determination: the process of separating a retrofit's (energy conservation measure's) effectiveness from a facility's energy use pattern. It involves measurements of physical conditions and analysis of resultant data.

savings measurement approach: the estimation of energy and demand savings associated with an energy conservation measure for a piece of equipment, a subsystem, or a system. The estimated savings are based on some kind of measured data from before and after the retrofit and may be calculated using a variety of engineering techniques. There are several different savings measurement approaches. Three generic (i.e., not project specific) approaches are described in this document: whole building metered approach, retrofit isolation, and whole building calibrated simulation.

system: any piece of equipment (e.g., fan, pump, motor, etc.) or pieces of equipment working together (e.g., heating system or electrical circuit).

uncertainty: the range or interval of doubt surrounding a measured or calculated value within which the true value is expected to fall within some degree of confidence.

uncertainty analysis: (1) a procedure or method by which the uncertainty of a measured or calculated value is determined; (2) the process of determining the degree of confidence in the true value when using a measurement procedure(s) and/or calculation(s).

utility meter: the meter used to calculate a monthly energy and/or demand charge at a specific utility/customer connection; more than one may be installed per customer and per site due to different supply voltages, capacity requirements, physical separation distances, installation periods, or for specific customer requirements or utility programs.

whole building calibrated simulation approach: the savings measurement approach defined in ASHRAE Guideline 14, which involves the use of an approved computer simulation program to develop a physical model of the building in order to determine energy and demand savings. The simulation program is used to model the energy used by the facility before and after the retrofit. The pre- or post-retrofit models are developed by calibration with measured energy use and demand data and weather data.

whole building metered approach: the savings measurement approach defined in ASHRAE Guideline 14 that determines energy and demand savings through the use of whole facility energy (end-use) data, which may be measured by utility meters or data loggers.

5. REQUIREMENTS AND COMMON ELEMENTS

Clauses 5.1 and 5.2 define and summarize the common elements of the three approaches for measuring savings, so that the subsequent Clause 6 can focus on the unique aspects of each approach. Clause 5.3 defines the mandatory elements of any savings determination activity claiming compliance with this guideline. Table 5-1 summarizes mandatory issues faced in choosing among four compliance paths. Clause 5.4 recommends appropriate steps in designing a savings determination process and presents nonmandatory issues to be considered when selecting a compliance path. Clause 5.5 provides recommendations for the ongoing management of the savings determination process.

5.1 Approaches

The three approaches to determining savings use similar concepts in savings computation. They differ in their ways of measuring the actual energy use and demand quantities to be used in savings determination. This clause summarizes the three approaches for determining energy and demand savings.

5.1.1 Whole Building Approach. The whole building approach uses a "main" meter to measure the energy flow to the whole building, a group of buildings, or separate sections of a building. Energy flow is usually electric, gas, oil, and thermal. ECMs may have been applied to one or more of the systems served by the meter. This approach may involve the use of monthly utility bill data or data gathered more frequently from a main meter.

5.1.2 Retrofit Isolation Approach. The retrofit isolation approach uses meters to isolate the energy use and/or demand of the subsystems (e.g., lighting, chiller, boiler) affected by the ECM from that of the rest of the facility. These measurements may be made once before and once after the retrofit, periodically, or continuously. Savings derived from isolated and metered systems may be used as a basis for determining savings in similar but unmetered systems within the same facility providing they are subjected to similar operating conditions throughout the baseline and post-retrofit periods.

5.1.3 Whole Building Calibrated Simulation Approach. The whole building calibrated simulation approach involves the use of a computer simulation tool to create a model of energy use and demand of the facility. This model, which is typically of pre-retrofit conditions, is calibrated or checked against actual measured energy use and demand data and possibly other operating data. The calibrated model is then used to predict energy use and demand of the post-retrofit conditions. Savings are derived by comparison of modeled results under the two sets of conditions or by comparison of modeled and actual metered results.

5.2 Common Elements of all Approaches.

Common elements of the three approaches for determining savings are presented below. Unique elements are presented in clauses 6.1 through 6.3.

5.2.1 Selecting Relevant Independent Variables. The independent variables are basically the forcing functions of the energy-using system. A proper analysis of any system requires that the most significant independent variables be identified, measured over the periods of interest, and then considered in any savings computation. Examples of significant independent variables include weather, occupancy, the number of items produced in an industrial facility, and the occupancy rate of a hotel. Variables that are unaffected by the retrofit but that are expected to change between or during the baseline and post-retrofit periods should be tested for their significance to savings uncertainty.

Weather is often the most important independent variable, affecting most of the systems covered under this guideline. Temperature, humidity, cloud cover, and wind can all influence energy use and demand.

Occupancy is another common independent variable affecting building energy use and demand. Changes in occupancy occur hourly, daily, weekly, seasonally, and as occupant operations change. Occupancy can be determined in a variety of fashions ranging from floor area rented through restaurant sales and hotel guest room sales.

The type and amount of weather or occupancy data used in determining savings depends upon the length of the savings measurement period, the availability of the data, the fraction of expected savings, and the desired level of uncertainty in determining savings.

Usually the independent variables used to adjust measured data do not account for 100% of the variation in energy use or demand. Minor changes to the facility or its operations, which go unnoticed, cannot be accounted for in the savings computations. Unaccounted for variable(s) are a primary source of uncertainty in any computed savings (see clause 5.2.11).

Selection of independent variables that substantively affect energy use and/or demand requires full understanding of how the facility uses energy and how the ECM acts on this energy use. All reasonable variables should be tested, using such parameters as the "t-test" to determine which variables are substantive.

5.2.2 Selecting the Baseline Period. Generally the period immediately before retrofit is preferred as the baseline period since its operations are most likely representative of the post-retrofit period. Also, since operating conditions of the most recent period are most easily remembered by operating staff, the most recent period is least likely to introduce bias or error from unaccounted for factors.

The range of conditions encountered by the affected energy-using system(s) should govern the length of the baseline period. Baseline periods, which span all modes of system operation (e.g., summer and winter or maximum and minimum hotel occupancy) are needed to reduce uncertainty in computed savings.

Care should be used to ensure that baseline periods contain samples of each operating mode in proportion to normal facility cycles of energy use. For example, a facility that operates on an annual cycle in response to weather should have a baseline period of a full year. When less than 12 months of data is available, selected periods should represent each season, without over- or underrepresenting any one mode of operation. Where more than a continuous 12 months of data are available, caution should be exercised to ensure that no time period is overrepresented. Balanced representation of all operating modes can be achieved by restricting baseline periods to an integral number of continuous 12-month periods (e.g., 12, 24, 36 months), not partial years (e.g., 13, 22, 30 months).

5.2.3 Documenting Baseline Conditions. During the post-retrofit period there may be changes in the design or use of the building that invalidate the baseline model. In order to provide a proper basis for future adjustments, appropriate operating conditions during the baseline period shall be recorded. The conditions to be recorded depend on the facility and its operation and the methods to be used to detect changes. However, the types of information normally required as a minimum are:

- occupancy pattern, density, schedule, and type, for each of the typical seasons
- throughput or other plant loads on typical and average days in each operating mode
- operating schedules and key setpoints of energy-using systems for all operating modes
- spot measurements under known operating conditions, where separate circuits serve distinct types of constant loads
- nonroutine functions of the facility, their dates and impacts on operations
- the nature and timing of any breakdown of significant energy-using equipment
- equipment nameplate data, except where changes are likely to be easily noticed and documented, for example, addition of more space or new services

When the only way to determine that a change has happened beyond the known retrofit(s) is to re-audit all the equipment, then all baseline equipment nameplates must be recorded before retrofit. Where there is a possibility of future equipment removal, replacement, or addition, without the full knowledge of the parties interested in the savings determination, a record shall be made of the make and model of all significant energy-using equipment in place during the baseline period. Baseline conditions shall be recorded for all the energy-using systems served by the meters to be used in the savings determination. Annex C examples contain descriptions of the information contained in the record of baseline conditions.

5.2.4 Setting the Duration of the Post-Retrofit Measurement Period. Variables used in computing savings shall be measured over a period of time that is long enough to

1. encompass all operating modes of the retrofitted system(s),
2. span the full range of independent variables normally expected for the post retrofit period, and
3. provide the intended level of certainty in the reported savings.

5.2.5 Selecting Measurement Equipment. All meters for measuring energy use, demand, or independent variables introduce some error. Meter error can be a significant factor affecting the uncertainty in computed savings. The number and location of the measurement devices also influence the level of uncertainty. The costs of the measurement equipment should be assessed in the measurement and verification plan outlined in Clause 5.4. Clause 7 and Annex A summarize key factors to consider in selecting measurement equipment.

Where the energy use of a system must be isolated from that of the rest of the facility (retrofit isolation approach), it is vital to identify and measure all secondary energy flows between the system and its surroundings.

5.2.6 Weather Data. Where on-site measurement of weather is impractical, the source of weather data shall be the nearest available weather station employing measurement techniques equivalent to those defined by the National Oceanic and Atmospheric Administration for "Class A" sites in the United States. (NOAA data are available from NOAA's National Climatic Data Center, 191 Patton Ave, Asheville NC. See also <www.ncdc.noaa.gov>.) Such sites are often located at airports and operated by the government. In the United States and Canada, final published versions of government weather observations can be treated as the definitive source.

Where a nearby weather station is unavailable, a more distant station may be used if its weather pattern is well correlated to the pattern at the particular facility, even if the total heating or cooling conditions are somewhat different.

If on-site measurement of temperature is used, the data shall be recorded in the pre-retrofit and post-retrofit periods using the same instruments, at the same location. It is also advisable to periodically check on-site weather data against the nearest public weather station data to check for drift and/or instrument failure. The error introduced by on-site measurement of this independent variable must be considered (see clause 5.2.11.2), except when following the whole building prescriptive path. The measurement devices must also conform to the calibration requirements in Clause 7.

5.2.7 Billing Demand. Billing demand is a quantity that is used by many utilities in computing bills for electricity, gas, or district heat supply. It may be different from the simple metered peak demand, requiring that determinations of savings recognize the differences that apply to each utility account.

Billing demand can be a fixed quantity (contract demand) associated with a negotiated capacity installed by the utility. Alternatively it can be measured each billing period as the highest usage rate during the period (peak demand). Some utility supply contracts involve a combination of both contract and peak demand quantities for determining billing demand.

Two common examples of how billing demand is different from peak demand are:

- Electrical billing demand is determined by increasing peak demand beyond that metered when power factor is below a prescribed level.
- Electrical billing demand is determined as the higher of contract demand and 60% (for example) of the highest of the previous 12 months' peak demands.

Demand savings determinations shall take into consideration all terms in the utility supply contract before computing the reduction in billing demand. Mathematical modeling of baseline demand should be applied to peak demand data as measured, before applying terms reflecting the utility's algorithm for determining billing demand. Demand savings can be high risk, depending upon the rate structure in use by the provider.

Electric demand, in kW or kVA, is usually metered over a fifteen-minute interval, though one-, three-, five-, and thirty-minute intervals are also used. Metering intervals may be fixed, sliding window, or instantaneous. The fixed interval uses the stated period as the measurement period. The sliding window interval uses a subset of the window interval to "slide" the interval in time. For example, a fifteen-minute sliding window interval may use one-, three-, or five-minute "subintervals" to accumulate the total demand for the fifteen-minute period. A new value for the fifteen-minute period is calculated every subinterval time. Instantaneous billing periods are usually one- or three-minute intervals. Natural gas demand is usually measured over a 24-hour period.

Demand meters installed to submeter electricity shall use the same or shorter metering interval as the supplying utility meter. The peak demand shall be measured at the same time as the utility meter's peak demand is measured, in order to measure demand coincident with the utility meter. A retrofit's reduction in electrical load may not necessarily be fully reflected in reduced peak demand, since the time of post-retrofit peak may have shifted to a former secondary peak.

Where a utility bill shows that energy use was estimated, a valid demand meter reading is usually not available.

All data needed for determining billing demand may not be shown on the utility bill. The utility company may need to provide extra information, such as factors and procedures used in billing and/or the time of monthly peak.

5.2.8 Calculations. Conditions such as weather and usage that govern energy use or demand are usually different between the baseline and post-retrofit periods. Measured use and demand must be normalized to a common set of conditions in order to report savings properly. The selection of that common set of conditions for normalization is discussed in clause 5.2.8.1.

The changes in conditions can be either routine or nonroutine. Routine changes, such as weather, occupancy, or hours of operation, which vary from one period of time to another, are those that can be anticipated and that can be readily documented. Calculations involving routine changes are discussed in clause 5.2.8.2. Nonroutine changes, such as change in building use from office to warehouse, follow no expected pattern and often require special effort for documentation. Adjustments for nonroutine changes are discussed in clause 5.2.8.3.

5.2.8.1 Selecting a Common Set of Conditions. To be comparable, baseline and post-retrofit period energy use and demand data must be projected to the same set of conditions. These conditions may be those of the post-retrofit period, a typical or average set of conditions, or the baseline period. The selection of the set of conditions establishes the type of savings that will be reported, as noted below.

a. Using actual post-retrofit period conditions, the reported saving is the avoided energy use of the post-retrofit period. This is the most typical approach, as it provides results consistent with actual energy use costs experienced after the ECM is installed.

b. Using a typical or average set of conditions, the reported saving is what would have happened if the facility had experienced that typical set of conditions.

c. Using actual baseline period conditions, the reported saving is the reduction from the use and demand level for operating conditions of the baseline period.

Even when the ECM(s) perform consistently, computed savings, when adjusted to post-retrofit conditions (a), will change as conditions change. However, when adjusting to a fixed set of conditions (b) or (c), computed savings will be steady when the ECM(s) perform consistently.

When adjusting baseline data to the post-retrofit period condition (a), projected baseline data and savings can be determined immediately after each measurement of post-retrofit energy use or demand. When adjusting to typical or baseline conditions (b) or (c), savings cannot be determined until after a mathematical relationship has been determined between the post-retrofit period use and its governing variables. This relationship must be established for each set of post-retrofit period data (typically a full cycle of operating conditions, usually a year where weather is the governing variable).

This guideline's analysis methods are based on the most common form of adjustment, namely, to post-retrofit period conditions (a). However, except where noted, the concepts presented here may be changed to allow adjustment to either typical or baseline period conditions.

5.2.8.2 Routine Calculations. A baseline model must be developed to correlate actual baseline energy use and/or demand with substantive fluctuating independent variables (clause 5.2.1.). This model is then regularly applied in an algorithm for savings determination, to derive energy use under post-retrofit period conditions.

A wide variety of modeling techniques may be used, ranging from simple averaging to regression analysis and hourly simulation. For any given set of data, some techniques may more faithfully predict a period's actual energy use than others. The modeling method chosen shall be consistent with the intended uncertainty of the savings determination and shall contain no net determination bias (see clause 5.2.10).

5.2.8.3 Baseline Adjustments. When changes are made to a facility's use or operations, the baseline model usually needs to be adjusted. These situations commonly arise from renovations, expansion, changes in usage, or addition of new equipment. Even the gradual addition of minor electrical equipment over an extended period may warrant baseline adjustment.

When there is a permanent change to the facility (other than the ECM(s) being assessed), the energy use and demand impacts of the change shall be determined by specific measurements and/or engineering calculations that reflect baseline conditions. The impact of the changes shall be reflected in a direct modification to the baseline model. The modification shall account for the impact under conditions of the baseline period.

Some changes in facility operations are only temporary in nature, such as where energy-using system services are curtailed due to equipment breakdown or suspended operating procedures. In such situations, the algorithm for savings determination may be temporarily supplemented with specific measurements and/or calculations to account for the change in the relevant period. These supplementary calculations shall be shown to fully account for the change.

Baseline adjustments may be recognized as necessary long after the actual change. It may also be known when the baseline model is being developed that the normal pattern of baseline conditions changed during the baseline period. In this latter case, unadjusted data shall be used to demonstrate compliance under clause 5.3.2, before any baseline adjustments are made.

The uncertainty added by these specific measurements and/or engineering calculations shall be reflected in the overall reported level of uncertainty assigned to each savings measurement under one of the performance compliance paths (see clause 5.2.11.4.)

5.2.9 Missing Data. Savings determined in one time interval shall not be used as a basis for determining savings in another time interval. However, in any of the performance compliance paths, missing data from the post-retrofit period may be estimated from at least 12 months of measured data using statistically valid engineering techniques, providing the subsequent calculation of the level of uncertainty in the reported savings reflects the appropriate change in the level of certainty.

5.2.10 Net Determination Bias. The necessary assumptions and the unavoidable errors in metering of energy use and demand introduce random error and bias into the computed savings. However, modeling and computations used to calculate savings should not add any more error or bias than might be generated by the computational accuracy of modern computational equipment for the whole building and retrofit isolation approaches. For the whole building calibrated simulation approach, modeling error is constrained by the calibration requirements of this guideline.

Computational methods used in the whole building and retrofit isolation approaches include three steps:

1. Development of the mathematical model of the baseline.
2. Filtering that may be applied to post-retrofit independent variable data.
3. Application of the possibly filtered post-retrofit independent variable data to the baseline model to determine the baseline energy use or demand adjusted to post-retrofit conditions.

Together these steps are defined herein as the algorithm for savings determination. Provided all steps are consistent with each other, only rounding errors will be added by the computational methods. For example, the same logic must be used in filtering post-retrofit data as is used in developing the model. Rounding errors should be insignificant so that no error is added by computational methods. In this guideline, such situation is defined as one with no "net determination bias."

The algorithm for savings determination used in whole building and retrofit isolation approaches shall be tested for net determination bias. The net determination bias test (see definitions) shall apply the baseline independent variable data to the algorithm for savings determination to re-compute an algorithm-determined baseline energy usage or demand for each of the n baseline data points (i). These re-computed quantities are then compared to the actual baseline energy usage or demand (i) in the baseline period to derive the net determination bias, as shown below:

$$\text{Net Determination Bias} = \frac{\sum^{n}(e_i - \hat{e}_i)}{\sum^{n} e_i} \times 100$$

Net determination bias shall be no more than 0.005% for whole building and retrofit isolation approaches.

5.2.11 Savings Uncertainty Calculations. This guideline presents simplified methods of assessing the quantifiable uncertainty in savings computations. Other uncertainty analysis methods are deemed compliant with this guideline if they can be shown to be relevant to the situation and use methods presented in published statistical textbooks.

Three primary sources of quantifiable uncertainty in savings determination are discussed here along with key methods for computing their impact as noted below:

- Sampling uncertainty (clause 5.2.11.1 and Annex B.2.4.1)
- Measurement equipment error (clause 5.2.11.2, Annex A, and Annex B.2.4.2.)
- Modeling uncertainty (clause 5.2.11.3 and Annex B)

Equations 5-6 and 5-7 in clause 5.2.11.4 consolidate these uncertainties for constant and varying baseline use, respectively. Annex B provides further background on these derivations of the uncertainty in computed savings.

Other types of uncertainty are not quantifiable. These include such systematic errors as human errors and errors of technique. Additional random or accidental errors include errors of judgment and unaccounted for changes in conditions. In addition, there are illegitimate errors such as mistakes, such as incorrect placement of transducers. Such sources of uncertainty may not lend themselves to explicit quantitative uncertainty calculations as discussed below. Nevertheless, their existence should be recognized, and their range of possible impacts presented in the measurement and verification plan.

Many methods shown here for the three categories of quantifiable errors are simplifications of strict statistical theory, for general application. These methods are shown so that practitioners can easily make reasonable estimates of the level of uncertainty in computed savings.

Terminology

q = number of randomly selected items from a population of Q items

Q = total number of pieces of equipment in a group to be sampled

F = approximate percentage of the baseline energy use that is saved. This percentage should be derived for the m periods of the reporting period. Before savings are actually achieved, the predicted savings may be used in computing F for purposes of designing the savings determination algorithm.

m = number of periods (months, weeks, days, hours) in the post-retrofit savings reporting period

n = number of data points or periods in the baseline period

n' = number of independent observations in a total of n observations.

n' is calculated as $n \times \frac{1-\rho}{1+\rho}$, where ρ is the autocorrelation coefficient of the series of n observations at lag 1. ρ is the correlation coefficient derived from performing a regression of the series of n observations against the same data series offset by one time step. The correlation coefficient is $\sqrt{1 - \left[\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2}\right]}$

For monthly data, this guideline permits an assumption that ρ is 0 so n' is equal to n.

p = number of parameters or terms in the baseline model, as developed by a mathematical analysis of the baseline data.

$RE_{instrument}$ = relative error in an instrument's measurement of a value, determined at the instrument manufacturer's rating point r_{rating}, expressed as a percentage.

$\bar{r}$ = mean value of a series of instrument readings

r_{rating} = reading of an instrument at the point at which its manufacturer quotes its relative error (RE) (normally full scale)

t = t statistic found in statistics textbooks. Selected values are shown in Table 5-1 for various confidence levels and values of (n-p).

TABLE 5-1
t-statistic

n-p	68% Confidence	80% Confidence	90% Confidence	95% Confidence
5	1.00	1.48	2.02	2.57
10	1.00	1.37	1.81	2.23
15	1.00	1.34	1.75	2.13
20	1.00	1.33	1.73	2.09
25	1.00	1.32	1.71	2.06
Infinite	1.00	1.28	1.65	1.96

U	=	relative uncertainty in a reported energy saving, expressed as a percentage of the savings
U_s	=	uncertainty created by sampling, expressed as a percentage of the mean
U_{iv}	=	savings uncertainty created by the error in measurement of post-retrofit period independent variables, expressed as a percentage of the savings (see clause 5.2.11.2)
y	=	dependent variable of some function of the independent variable(s)
$\bar{y}$	=	arithmetic mean of the sample of n observations
$\hat{y}$	=	regression model's predicted value of y

5.2.11.1 Sampling Uncertainty. The relative uncertainty created by estimating the mean ($\bar{y}$) of a population of Q items from a random sample of q items with values y_i is:

$$U_S = \frac{100}{\bar{y}} \times \sqrt{(1 - q/Q)\left[\sum_{i=1}^{n} (y_i - \bar{y})^2/(q-1)\right]/q} \tag{5.1}$$

5.2.11.2 Measurement Equipment Error. The equipment used to measure physical quantities produces both measurement and data capture errors due to the calibration, range, and repeatability of the equipment and installation effects. These factors influence the uncertainty of values reported for energy use and other variables.

This guideline assigns zero measurement error for the following items:

1. Energy use, demand, and independent variables included in a regression model for the baseline period. These errors are inherently assessed by the coefficient of variation determined for the baseline model (clause 5.2.11.3), assuming there is no bias in the reported data.
2. Post-retrofit period energy use data that is reported on utility bills.
3. Post-retrofit period weather data published by a government-operated weather reporting service in the United States or Canada.

Measurement error shall be assessed for non-billing energy use meters, adjustments for inventories of stored energy quantities, and measurements of post-retrofit independent variables. Errors shall be estimated in terms of both accuracy and confidence levels. Manufacturer's literature or a series of field measurement system verification tests will provide estimates of accuracy, termed relative error ($RE_{instrument}$), at some rating point (r_{rating}), usually full scale. Where accuracy or confidence intervals are unknown, the values shown in Annex A5 may be used, assuming a 68% confidence interval. The source of measurement error estimates shall be indicated.

The combination of several components in measuring any value will combine the individual errors of each. The $RE_{instrument}$ of C dependent variables can be combined into a final value for overall instrument error using equation 5-2, where $\bar{r}$ represents the mean reading on any instrument.

$$RE_{instrument} = \frac{\sqrt{\sum_{i=1}^{C} (RE_{instrument} \times r_{rating,\,i})^2}}{\sum_{i=1}^{C} \bar{r}_i} \tag{5.2}$$

Error in measuring post-retrofit independent variables shall not be combined with any error in metered energy use. The impact of this independent variable error (U_{iv}) shall be simply assessed by computing the savings twice: once with the independent variables at their maximum values and once with them at their minimum values for the stated confidence interval. The difference between these two computed savings defines the total span of the extra uncertainty created by the error in measuring independent variables. The maximum and minimum independent variable values used shall be stated.

5.2.11.3 Modeling Uncertainty. This guideline uses the following three indices to represent how well a mathematical model describes the variability in measured data. These indices shall be computed for the single mathematical model used to describe the baseline data from all operating conditions (i.e., both summer and winter shall be consolidated in one model for evaluating these indices).

1. Coefficient of variation of the standard deviation (CVSTD)

$$CVSTD = 100 \times [\sum (y_i - \bar{y})^2/(n-1)]^{1/2} \bar{y} \tag{5.3}$$

2. Coefficient of variation of the root mean square error (CVRMSE)

$$CVRMSE = 100 \times [\sum (y_i - \hat{y}_i)^2/(n-p)]^{1/2}/\bar{y} \tag{5.4}$$

3. Normalized mean bias error (NMBE)

$$NMBE = \frac{\sum^{n} (y_i - \hat{y}_i)}{(n-p) \times \bar{y}} \times 100 \tag{5.5}$$

For calibrated simulations, the CVRMSE and NMBE of modeled energy use shall be determined by comparing simulation-predicted data ($\hat{y}$) to the utility data used for calibration (y_i), with $p = 1$.

5.2.11.4 Computing Savings Uncertainty. Overall savings uncertainty is estimated by considering sample size (q, Q), measurement error ($RE_{instrument}$ and U_{iv}), modeling uncertainty (CV), the length of the savings determination period (m), and the fraction of baseline energy saved (F). Overall savings uncertainty shall be estimated as follows:

1. Adjust the measurement and modeling uncertainties to a common confidence interval, using the ratio of the relevant t-statistics in Table 5-1.
2. Use equation 5-6 or 5-7 below, as appropriate. The Table 5-1 t-statistic used shall match the confidence levels used in assessing the measurement and modeling uncertainties.
3. Report the confidence level with the uncertainty.

4. Uncertainty associated with any baseline adjustments (clause 5.2.8.3) shall be included by treating it as part of the error in post-retrofit energy use measurements, using equation 5-2.

In cases where the baseline energy use or demand is essentially the same for all periods or unaffected by any known independent variables (e.g., a lighting circuit's energy use read monthly):

$$U = \frac{t}{F}\sqrt{\frac{CVSTD^2}{m} + U_S^2 + RE_{instrument}^2} \qquad (5.6)$$

In cases where baseline energy use or demand varies from period to period in response to known independent variables,

$$U = \frac{t}{F}\sqrt{\frac{CVRMSE^2}{m} \times \left[\frac{n}{n'}\left(1.6 + \frac{3.2}{n'}\right)\right] + U_S^2 + RE_{instrument}^2 + U_{iv}^2} \qquad (5.7)$$

Equation 5-7 simplifies to equation 5-7.1 for the common situation where no sampling is done ($q = Q$), utility bills are the source of all energy use data ($RE_{instrument} = 0$ and $n = n'$), and United States or Canadian government published weather data are used as the only independent variable ($U_{iv} = 0$). Figure B-1 and Table B-2 in Annex B portray this relationship at 68% confidence and a 12-month baseline period.

$$U = t \times \frac{1.26 \times CVRMSE}{F} \times \sqrt{\frac{n+2}{n \times m}} \qquad (5\text{-}7.1)$$

It should be noted that savings uncertainty estimates using these formulae for the calibrated simulation approach apply only to the total savings determined for a meter, not to the savings of individual retrofits. Also t should be determined for calibrated simulations using $p = 1$.

5.2.11.5 Managing Uncertainty. When planning a retrofit project, a target savings uncertainty level should be established. Then equation 5-6 or 5-7 can be used to evaluate feasible combinations of model CV(RMSE), instrument error, sample size, post-retrofit period length, and expected savings fraction. The costs of feasible combinations of savings determination characteristics can be evaluated to find the lowest-cost means of achieving the target uncertainty.

It should be noted that uncertainty (U) declines as the savings reporting period (m) lengthens. However, compliance with this guideline's maximum level of uncertainty is determined from annual savings only.

Examples of the use of these equations are shown in Annexes B and C.

5.3 Compliance Requirements.

To claim compliance with this guideline, the savings measurement shall meet the basic and specific requirements shown in clauses 5.3.1 and 5.3.2, respectively. Examples of compliant savings measurement processes are listed in Annex C. The general methodology of all compliant methods is summarized below:

a. Prepare a measurement and verification plan, showing the compliance path chosen, the metering and analysis procedures

b. Measure the energy use and demand and the selected independent variables (see clauses 5.2.1 and 5.2.5) driving energy use in the baseline period. Document baseline conditions (see clause 5.2.3).

c. Measure the same energy use and demand and independent variables in the post-retrofit period.

d. Project the baseline and/or post-retrofit period energy use and demand measurements to a common set of conditions (see clause 5.2.8.1).

e. Subtract the projected post-retrofit period use and billing demand from the projected baseline period use and billing demand to determine the savings. For performance path compliance, the level of uncertainty must be less than one-half of the total savings reported in the post-retrofit reporting period.

5.3.1 Basic Requirements

a. Prepare a measurement and verification plan as defined in clause 5.4.1, before retrofit implementation.

b. Measure and report post-retrofit energy use and demand, independent variables, and conditions used in the algorithm for savings determination.

c. Apply the algorithm for savings determination for all periods where independent variables are no more than 110% of the maximum and no less than 90% of the minimum values of the independent variables used in deriving the baseline model.

d. For periods not complying with (c) above, any savings report shall note that the independent variable(s) for that period are beyond the range of applicability of the model derived from baseline data.

Determine and document the effect(s) of any changes to baseline conditions.

5.3.2 Approach Specific Requirements. There are four compliance paths for the three approaches. Each path has its own requirements as described below. Since some of the requirements are similar but not identical, Table 5-2 presents a summary of the key path specific compliance requirements.

5.3.2.1 Whole Building Prescriptive Path. This path shall be used when no uncertainty calculations are included with savings reports. Compliance with this path requires the following:

a. Expected savings shall exceed 10% of measured whole building (or relevant submetered portion of whole building) energy use or demand.

b. The baseline period shall span a continuous period of at least 12 months without any gaps in energy use or demand or independent variable data.

c. There shall be a minimum of nine valid measured data points in the baseline data.

d. No data points shall be eliminated from the baseline period.

e. The baseline model shall have a maximum CV(RMSE) of 20% for energy use and 30% for demand quantities when less than 12 months' worth of post-retrofit data are available for computing savings. These requirements are 25% and 35%, respectively, when 12 to 60 months of data will be used in computing savings. When more than 60 months of data will

This table is an aid to understanding only. Requirements are defined in clause 5.3.

TABLE 5-2
Path Specific Compliance Requirements

		Minimum Requirements for Each Path			
		Whole Building		Retrofit Isolation	Whole Building Calibrated Simulation
		Prescriptive	Performance	Performance	Performance
1	Measured data available from:	Baseline and post-retrofit	Baseline and post-retrofit	Baseline and post-retrofit	Baseline and/or post-retrofit. Report source and accuracy
2	Energy use measurement type	Continuous	Continuous	Note 3	Continuous
3	Minimum period spanned by baseline data	12 months	Full range	Full range	12 months
4	Minimum number of valid data points	9			12
5	Allow elimination of data?	No	Explain. Max 25%	Explain	
6	Algorithm for savings determination	Net determination bias <0.005%	Net determination bias <0.005%	Net determination bias <0.005%	
7	Baseline model uncertainty	Note 1			Note 2
8	Expected savings	>10%			
9	Uncertainty analysis		Required	Required	Required
10	Number and type of ECM	>1 or complex	>1 or complex	1	>1 or complex
11	ECM interaction with energy use of the rest of the building	Can be significant	Can be significant	None	Can be adequately simulated
12	Special skills of personnel				Five years' computer simulation experience
13	Maximum level of uncertainty		50% of annual reported savings at 68% confidence	50% of annual reported savings at 68% confidence	50% of annual reported savings at 68% confidence
14	Use of sampling	Not allowed	Note 4	Note 5	Not allowed
15	Minimum data interval	1 day			
16	Modeling tool				Simulation (hourly if include demand), public domain or commercially available, plus. Report version number and provide input file.
17	Allow estimate of post-retrofit data	No	From data spanning missing data	From data spanning missing data	From data spanning missing data

Notes	
1	For <12 month post-retrofit savings reporting period length: max. 20% (energy use), 30% (demand)
	For 12-60 month post-retrofit savings reporting period length: max. 25% (energy use), 35% (demand)
	For >60 month post-retrofit savings reporting period length: max. 30% (energy use), 40% (demand)
2	For monthly calibration data 15% and NMBE 5%.
	For hourly calibration data 30% and NMBE 10%, if used.
3	If energy use measurement is not continuous, periodically measure demand and continuously record operating periods of relevant equipment.
4	Multiple similar facilities, providing sampling error is included in savings uncertainty calculation.
5	Multiple similar systems at one facility, providing sampling error is included in savings uncertainty calculation.

be available, these requirements are 30% and 40%, respectively.

f. The algorithm for savings determination shall comply with net determination bias test as defined in clause 5.2.10.

g. Savings shall not be reported for post-retrofit periods without valid measured data.

h. Measured hourly or more frequent data shall be averaged to intervals of at least one day in length.

5.3.2.2 Whole Building Performance Path. Compliance with this path requires the following:

a. The baseline data shall span the normal full range of all independent variables under normal facility operations.

b. Reasons shall be reported for data gaps, data elimination, or estimation of any actual measured data in the baseline or post-retrofit periods. No more than 25% of the measured data shall be excluded.

c. Where multiple similar facilities of one owner are involved, uncertainty and confidence calculations shall include the impact of any sampling techniques used.

d. The algorithm for savings determination shall comply with net determination bias test as defined in clause 5.2.10.

e. With each annual savings report, show at least the level of uncertainty and confidence interval in the savings determined during the post-retrofit period (see clause 5.2.11.4).

f. The level of uncertainty must be less than 50% of the annual reported savings, at a confidence level of 68%.

5.3.2.3 Retrofit Isolation Performance Path. Compliance with this path requires the following:

a. The baseline data shall span the normal full range of all independent variables expected to occur under normal facility operations.

b. A technique identified in Annex E shall be used.

c. Reasons shall be reported for data gaps, elimination or estimation of any actual measured data in the baseline or post-retrofit periods.

d. Estimation of missing data shall use actual data points that span the typical range of independent variables.

e. Where energy use measurement is less than continuous, periodic measurements shall be made of demand, and operating periods of relevant equipment shall be recorded continuously.

f. Where multiple similar systems at one facility are involved, uncertainty and confidence calculations shall include the impact of any sampling techniques used.

g. The algorithm for savings determination shall comply with net determination bias test as defined in clause 5.2.10.

h. With each annual savings report, show at least the level of uncertainty and confidence interval in the savings determined during the post-retrofit period (see clause 5.2.11.4).

i. The level of uncertainty must be less than 50% of the annual reported savings, at a confidence level of 68%.

5.3.2.4 Whole Building Calibrated Simulation Performance Path. Compliance with this path requires the following:

a. The simulation tool used to develop models for buildings shall be a computer-based program for the analysis of energy use in buildings. It shall be commercially available or in the public domain. The tool shall be able to adequately model the facility and ECM(s) (see clause 6.3.3.), performing calculations for each hour of the time period in question, e.g., for a one-year period the model shall perform 8,760 hourly calculations. In addition, it shall be able to explicitly model at least the following:

- 8,760 hours per year,
- thermal mass effects,
- occupancy and operating schedules that can be separately defined for each day of the week and holidays,
- individual setpoints for thermal zones or HVAC components,
- actual weather data
- user-definable part-load performance curves for mechanical equipment, and
- user-definable capacity and efficiency correction curves for mechanical equipment operating at non-rated conditions.

b. Provide a complete copy of the input data, indicating which data are known and which are assumed. Report the source of all data described as "known," and assess its level of uncertainty.

c. Report the name and version of simulation software used

d. Report the source and accuracy of the calibration data.

e. Calibration data shall contain at a minimum all measured monthly utility data from 12 bills spanning at least one year.

f. The computer model shall have an NMBE of 5% and a CV(RMSE) of 15% relative to monthly calibration data. If hourly calibration data are used, these requirements shall be 10% and 30%, respectively.

g. With each savings report, show at least the level of uncertainty and confidence interval for the annual savings determined during the post-retrofit period (see clause 5.2.11.4).

h. The level of uncertainty must be less than 50% of the annual reported savings, at a confidence level of 68%.

5.4 Design of a Savings Measurement Process

The design of a savings measurement process shall be documented in a measurement and verification plan as defined in clause 5.4.1. (See also *ASHRAE Handbook* 1995, chapter 37.) This plan should address the balance between the level of uncertainty and the costs of the process as presented in clauses 5.4.2 and 5.4.3. Clause 5.4.4 provides suggestions on choosing an approach, which may be considered in addition to the requirements of clause 5.3.

5.4.1 Measurement and Verification Plan. The design of a savings measurement process shall be documented in a savings measurement and verification plan before an ECM(s) is installed. The measurement and verification plan shall document the following:

a. The selected measurement approach and compliance path.

b. Baseline period data:

- Energy use and demand. Actual meter reading dates or times shall be recorded. With stored energy sources, shipment dates and volumes must be recorded along with period ending inventory levels.
- All independent variables selected for use in analyses and the basis for selection as well as the basis for not using any variables that may be reasonably considered. Measurement shall be made on the same day as meters are read for monthly quantities or the same hour for daily quantities.
- Baseline conditions as defined in clause 5.2.3.

c. The algorithm for savings determination, showing

1. the methodology to be used for all normal sets of post-retrofit conditions and
2. the means of dealing with each type of anomaly that was the subject of an exclusion or adjustment when developing the baseline model.

d. The measurement procedure as defined in clause 7.2 for any measurement equipment other than utility meters.

e. Quality control procedures (see clause 5.5.4).

f. The items shown in Table 5-3 for the intended compliance path.

g. The savings reporting frequency and format.

5.4.2 Establishing Levels of Uncertainty. The interests of all parties should be considered before establishing the expected level of uncertainty for a savings measurement. For example, where payments are made for savings for a fixed period of time, there may be greater interest in lower levels of uncertainty than if payments cease after the total payment meets some agreed total amount.

Clause 5.2.11 and Annex B provide guidance for proper calculation of the level of uncertainty for savings measurements.

5.4.3 Cost. The annual cost of determining savings should normally be only a small fraction of the annual savings themselves. This cost constraint dictates the design of the savings measurement process. Careful planning is needed to constrain the cost of measurement, computation, and reporting of savings and uncertainty.

Some of the cost of measuring savings may be shared with other functions, such as operational monitoring or controls using the same measured data. Facility automation systems often present this opportunity.

Significant factors affecting the cost of savings measurement are

- number of pieces of equipment needed to measure energy use, demand, and independent variables and
- length of time required for savings measurement.

The choice of compliance path (clause 5.4.4) is a key determinant of the amount of measurement equipment and length of time. However, the complexity of the building or the ECMs and the nature of any contractual relationship between the facility owner and a contractor may also be factors.

TABLE 5-3
Path Specific Requirements of the Measurement and Verification Plan

	M&V Plan Shall Describe:	Whole Building		Retrofit Isolation	Whole Building Calibrated Simulation
		Prescriptive	Performance		
1	Baseline Model parameters, range of applicability, and CV(RMSE)	Yes	Yes	Yes	No
2	Name and version of software to be used for simulation	No	No	No	Yes
3	MBE and CV(RMSE) of computer baseline model relative to calibration data	No	No	No	Yes
4	Effectiveness of isolation metering, interactive effects included and excluded by the metering	No	No	Yes	No
5	Net determination bias of algorithm for savings determination	Yes	Yes	Yes	No
6	Expected level of uncertainty in savings determinations (see 5.2.11.4).	No	Yes	Yes	Yes
7	The possible impacts of unquantifiable sources of uncertainty (see 5.2.11.)	No	Yes	Yes	Yes
8	Methodology to be used in computing the level of uncertainty in future savings reports (see 5.2.11.4).	No	Yes	Yes	Yes

TABLE 5-4
Considerations in Selecting a Compliance Path

Considerations		Best Applications for Each Path			
		Whole Building		Retrofit Isolation	Whole Building Calibrated Simulation
		Prescriptive	Performance		
1	Ability to determine savings of individual ECMs	No	No	Yes*	Yes
2	Nature of possible future baseline adjustments	Minor but can be estimated adequately	Minor but can be estimated adequately	Complex, or effect on ECM performance is simple to estimate adequately	Many or complex
3	Impact of ECMs	Any component of the facility	Any component of the facility	No reduction of building envelope losses	Any component of the facility
4	Understanding by nontechnical personnel	Can be simple	Can be simple	Can be very simple	Difficult
5	Special skills of personnel			Metering systems	See Table 5-2
6	ECMs' interaction with the energy use of the rest of the facility	Can be complex	Can be complex	To be ignored or measured	Can be complex
7	Best length of post-retrofit period	Multiyear	At least one year	Representative periods	Maybe none

*. The cost of using the retrofit isolation path for multiple ECMs in the same facility should be compared to the cost of using the whole building or calibrated simulation paths.

For each piece of measuring equipment, cost is affected by the required accuracy of the meter, installation detail with re-calibration/removal facilities, and data telemetry. The ongoing costs of each meter will include maintenance and recalibration, meter reading, and data handling and storage. Use of utility company meters and public weather data sources can minimize many of these measurement-related costs while reducing uncertainty as noted in clause 5.2.11.2.

The cost of computing savings also includes the labor to derive the baseline model and to maintain it as adjustments are needed.

Generally, the more complex the system for measuring savings, the more explanations will be required to gain the understanding of all stakeholders. Therefore, designing a savings measurement process as simply as possible to meet the uncertainty target can minimize costs.

5.4.4 Choosing A Path. The choice of savings measurement path must consider both the equipment required and the calculations needed to report savings and meet the uncertainty target. These issues should be considered during the conceptual design of the retrofit project, including the uncertainty impact of possible variances in the performance of measurement or savings equipment. This way the trade-offs between cost and level of uncertainty are assessed before committing to a retrofit design.

Every project must find its own balance between the benefits and costs of measurement and resultant accuracy. Any of the paths can be implemented to suit a range of costs and certainties. Users are cautioned that even two well-experienced modelers will not generally determine the same savings amount, and sometimes there are significant differences.

Table 5-4 summarizes some key considerations in selecting a compliance path. These recommendations should be considered together with the requirements in Table 5-2.

Because of the trade-off between cost and uncertainty, the optimal approach for a specific project usually results from an iterative approach, where incremental improvements in accuracy are assessed relative to the increase in measurement cost. Such optimization requires that a value be placed on the level of accuracy. One way to accomplish this is to consider the uncertainty of the proposed approach by calculating results using the highest and lowest values in the confidence interval. The difference between these values can be translated into a dollar amount that is at risk. It can then be determined whether further expense for improving the savings measurement process is warranted to reduce this uncertainty.

The following example highlights key factors in selecting a path. Other examples are in Annex C.

> Consider a multi-faceted energy management project expecting to save 30% of a hospital's current fuel use (F=30). The parties interested in assessing the performance of the project wish to be reasonably assured, with 95% confidence, that there will be no more than 20% uncertainty in the annual reported fuel savings information.
>
> Since this is a multi-faceted project, without major changes expected in use or occupancy of the facility, the whole building approach is most suitable. Monthly utility data of the year immediately before retrofit are compared to weather data and other factors. By regression analysis it is found that by simply correlating government-reported heating temperature data with monthly gas usage, a model with a CV(RMSE) of 6% can be defined. Since savings exceed 10%, and the CV(RMSE) is less than 30%, the prescriptive path may be followed.
>
> However, an uncertainty calculation is needed to ensure that the 20% uncertainty specification is met (U=20). Equation 5-7.1 can be used because (a) utility metering will be used, (b) government-reported weather data will be used (5.2.11.2 iii), (c) monthly data are used so no autocorrelation exists ($n = n'$), and (d) no sampling procedures are to be used ($q = Q$). The baseline model is

derived from all 12 months (n=12) preceding retrofit (y = 2,560 + 33.91 * heating degree-days below 50°F). The model contains three parameters (2,560, 33.91, 50). The t statistic for 95% confidence and n-p = 9 is interpolated from Table 5-1 to be 2.3. The resultant annual (m=12) uncertainty (U) will be 18%. Therefore, the target uncertainty level will be met.

If the savings were to be assessed after just one month, equation 5-7.1 would show that the uncertainty at 95% confidence is 63% and the specification would not be met. Consideration may be given to using daily or hourly fuel use data, with additional well-correlated independent variables beyond temperature. The retrofits may also need to be separately assessed (retrofit isolation) to minimize the need to monitor and adjust for more independent variables that may dominate in a short period. Such a switch to the retrofit isolation approach may dictate that some of the energy savings from operational changes and measure interactions cannot be measured following the procedures in this guideline.

5.5 Implementation of the Savings Measurement Process

Before beginning any savings measurement process, the process must be designed as outlined in clause 5.4. The subsequent implementation of the process will require proper integration of hardware, software, and personnel to achieve design uncertainty levels in computed savings.

5.5.1 Hardware. Meters and measuring equipment involved should be commissioned and maintained to ensure they function within the limits contemplated in the measurement and verification plan. Data gathered should be regularly verified to identify any data loss or likely error. Equipment must be recalibrated as defined by the manufacturer. Clause 7 contains guidelines in these matters. The impact of any required recalibration should be reflected back onto any previously obtained baseline period data, possibly increasing the overall level of uncertainty.

5.5.2 Software. Computer methods developed for analyzing data shall be tested to demonstrate their ability to properly handle all potential combinations of input data. The methods shall identify periods where valid data are missing so that the associated increase in uncertainty can be determined.

5.5.3 Personnel. People involved with the savings measurement process range from the designer(s) of the ECM(s) and the measurement and verification plan, through those handling data, to hardware service mechanics, to those preparing savings reports. All should appreciate their role in maintaining the intended level of certainty. Adequate time should be allowed for all personnel to be trained and to perform their ongoing roles.

Nontechnical readers often use savings reports so the reports should include a simple presentation of the facts with a clear statement of the level of certainty as required herein. A layman's description of the savings determination approach can be helpful in ensuring correct understanding of routine savings reports.

5.5.4 Quality Control. The accuracy of any savings measurement process is dependent on the quality control of all data gathering and management processes. Procedures should be set up to catch any errors and inadvertent or unauthorized tampering of the data.

It is good practice to outline the processes that need to be followed in handling data and where and how the data are stored (both paper and electronic forms). ISO 9000 work instructions are often helpful in this area. Clause 7.6 lists appropriate verification techniques that may be used during real-time data gathering. Other quality control techniques are suggested below.

- Access for modifying data shall be restricted to properly trained persons with appropriate authority.
- Use computer software to check the accuracy and reasonableness of an entry. For example, meter readings can be used to verify usage values.
- Persons other than those directly involved in producing and reviewing the results shall regularly or on a spot basis check the data and resultant calculations.
- Regularly test the backup and restore procedures for electronically stored data.

Permanently store the measurement and verification plan, all raw data, baseline model development facts, baseline adjustment calculations, and any post-retrofit period data adjustments. This information shall be organized, protected from inadvertent tampering, and readily available throughout the life of a project.

6. SPECIFIC APPROACHES

6.1 Whole Building Approach

6.1.1 General Overview. The whole building approach, also called main meter approach, encompasses procedures that verify the performance of the retrofits for those projects where whole building pre- and post-retrofit data are available to determine the savings. This clause discusses methods using utility billing data (usually monthly data). Also discussed are methods that involve continuous measurements of whole-building energy use before the retrofit and continuous measurements of the whole building energy use after the retrofit on a more detailed measurement level (weekly, daily, or hourly).

Consumption and demand values taken from submeters are acceptable for use under the whole building approach, where the meter measures energy use of a significant portion of the building area or a group of subsystems (e.g., motor control center). The data shall meet all the requirements as for a utility meter. Submeters are particularly useful in multiple building sites served by one utility meter. Examples include university and college campuses, armed forces bases, and large industrial facilities.

6.1.2 Criteria for Whole Building Approach. It is most appropriate to use a whole building approach when the total building performance is to be calculated, rather than the performance of specific retrofits. There are two paths for the whole building approach, each having certain criteria and requirements for applicability.

6.1.2.1 Whole Building Prescriptive Path. This path is most appropriate where the expected savings are greater that 10% of the measured energy use or demand and where the

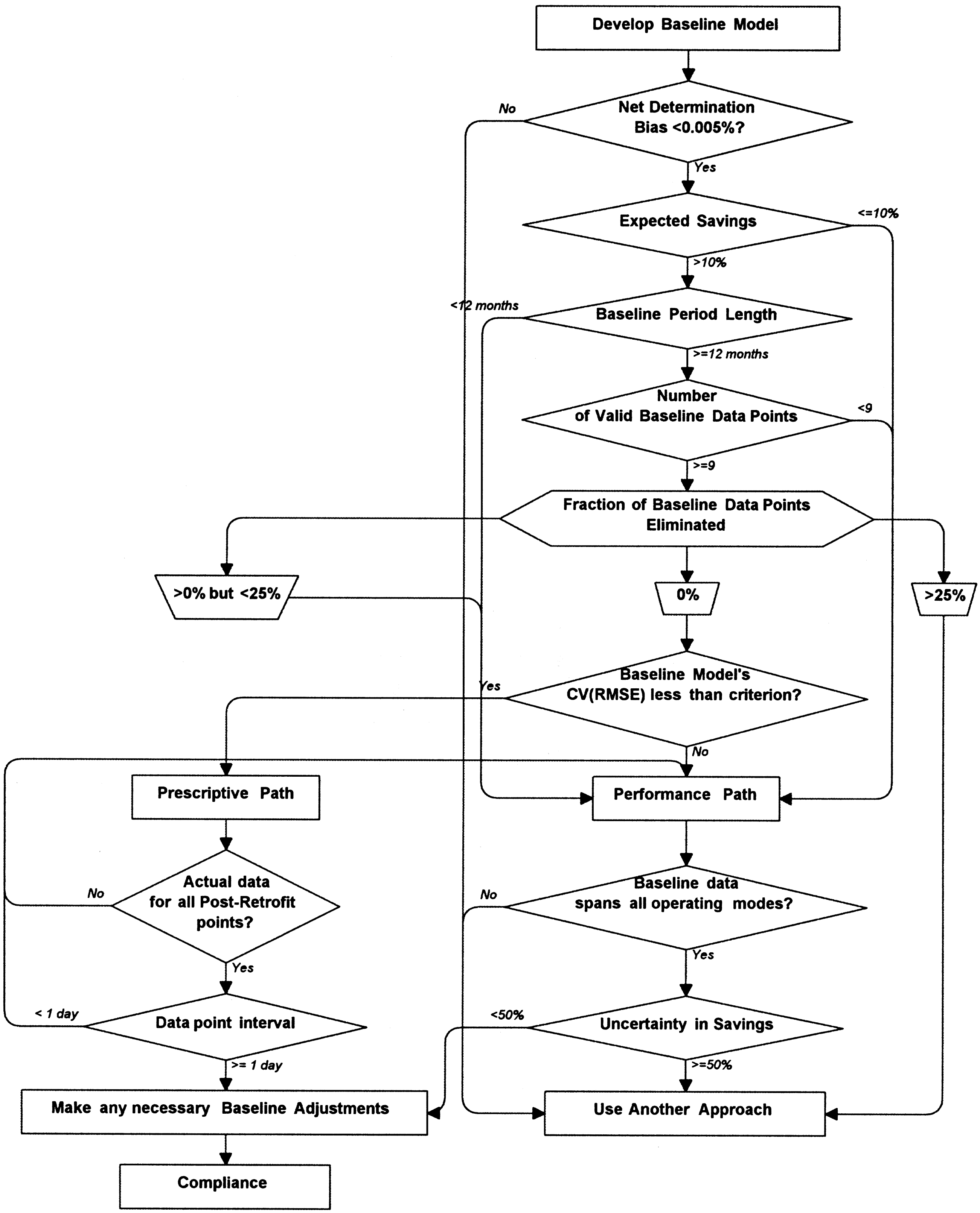

Figure 6.1-1 Flow chart for whole building approach.

data are continuous, complete with no data points to be excluded, and are expected to remain like this in the post-retrofit period.

6.1.2.2 Whole Building Performance Path. This path is most appropriate where the data are not continuous, have gaps, and are expected to have similar problems in the post-retrofit period.

6.1.3 Methodology and Calculations.

6.1.3.1 Overview of Methodology. There are two compliance paths that can be followed under this approach—prescriptive and performance. Each path has specific data requirements, as described in clause 5 of this guideline. Both of these paths follow the same methodology, namely:

- collect data on energy use, demand, and independent variable(s);
- determine the path and best statistical model;
- calculate energy and demand savings.

6.1.3.2 Collect Data.

6.1.3.2.1 Non-Stored Energy Sources. For electric, steam, and pipeline-supplied gas or other non-stored energy sources, the following information must be recorded:

a. The date of the meter readings
b. The amount of energy use measured for the utility billing period

6.1.3.2.2 Stored Energy Sources. For coal, liquid natural gas (LNG), oil, or other stored fuels, typically on site, two types of data are applicable—inventory readings and delivery information. More accuracy is achieved by using both types, but inventory readings can often be difficult to obtain. Only delivery information is required.

1. *Inventory Readings.* This involves measurements of the amount of fuel in storage at the start and end of a period and the amount used during that period.
   a. *The date of the inventory readings.* Inventory readings need to be conducted on a regular schedule; bi-monthly, monthly, semi-monthly, weekly, and daily are acceptable.
   b. *The change in inventory.* This is indicated by the amount of fuel in storage.
2. *Delivery Information.*
   a. *The date of the delivery.* These dates can be determined from delivery invoice information from the fuel supplier.
   b. *The amount of fuel delivered.* This information is obtained from the delivery invoice information from the fuel supplier.

The energy use for a particular time period can then be determined by calculating the change in inventory and adding the amount delivered.

6.1.3.2.3 Demand Data. For electric, steam, and pipeline-supplied gas or other demand measurements, the following information must be recorded:

a. The date of the meter reading
b. The amount of demand for the utility billing period

6.1.3.2.4 Time-of-Use Data. Many electrical utility companies have moved toward time-of-use, time-of-day, or real-time electricity pricing. In this situation, the electricity bill shows energy use in on-peak (daytime), off-peak (nighttime), and sometimes shoulder periods (evening and morning) for cost calculations. Customers are charged more for on-peak usage than off-peak usage. When this situation arises, several options are available, but some caution is needed.

Different baseline models can be derived for the different components. If hourly temperature readings are available, then the model may use the mean temperature or independent variable for the coincident period.

In some instances, a better model is achieved by summing up the components and using the total use in the analysis.

In many cases the baseline period does not have time-of-use components and the billing process changed in the post-retrofit period. In this case, dividing the baseline energy use into components, unless hourly records are available, is not allowed. The savings calculations shall use the sum of the components to derive the projected baseline energy use. It is important that this situation be recognized in any energy performance contract, as it will have a dramatic impact on the savings cost calculations.

6.1.3.2.5 Weekly, Daily, or Hourly Data. The use of more detailed energy use data may decrease the uncertainty in the computed savings. However, there is usually a need to track more independent variables to model the energy use and demand. In addition, the independent variables must be recorded at the same time intervals as the energy data.

Regression models using hourly data points are allowed; however, there are situations that warrant summing hourly data into subdaily (occupied/unoccupied periods) or daily.

6.1.3.2.6 Independent Variables. In many cases, the energy use and/or demand will depend on the change in an independent variable. The most common example is outdoor temperature, which will affect the energy used to supply heating and cooling to the building. There are other variables that can also affect the energy use and demand in buildings. Examples include:

- Number of meals served in a restaurant
- Number of occupants (hotel guests) in a building
- Number of items produced in an industrial facility

These independent variables must conform to the same data requirements as the energy use or demand specific to the two compliance paths in this approach.

6.1.3.2.6.1 Weather Data. If outdoor temperature is to be used as an independent variable that affects energy use and/or demand, then temperatures can be measured on site, or publicly available sources can be used. See clause 5.2.6 for more details.

6.1.3.2.6.2 Other Independent Variables. The data representing the independent variables are also required and must either

a. coincide with the reading dates of the energy use and demand data

OR

b. be recorded on a finer time increment than the energy use and/or demand to allow for division into billing periods.

For example, by recording other independent variables on a daily basis, it is a simple matter to calculate the total or average of the variable for the monthly time periods typical of utility energy use and/or demand measurements.

6.1.3.3 Select Baseline and Define Mode. A statistical analysis must be conducted on the energy use and demand as it relates to weather data and/or one or more independent variables. The most common technique is to use linear regression to correlate energy use or demand as the dependent variable with weather data and/or other independent variables.

Several different models are acceptable in developing an energy use baseline, as summarized in clause 6.1.3.7 and detailed in Annex D.

Each of these models will contain the following:

1. The form of the linear equation that describes the energy use as a function of the driving variable(s)
2. The coefficient(s) of each term in the equation
3. The value of CV(RMSE), which indicates the uncertainty inherent in the model.

The model must meet the CV(RMSE) or uncertainty requirements of clause 5.3.2.1. In most cases the model will take the form of a linear, multiple-variable equation:

$$E = C + B_1V_1 + B_2V_2 + B_3V_3 + ... \qquad (6.1\text{-}1)$$

where

E = energy use or demand estimated by the equation,

C = constant term in [energy units/day] or [demand units/billing period],

B_n = coefficient of independent variable V_n in [energy units/driving variable units/day] or [demand units/driving variable units/day],

V_n = driving variable.

For hourly models, the units are on a per hour basis.

In general, one would like a model selection procedure that is simple to apply and produces consistent, repeatable results. Several procedures have been recommended to select the best regression results. In general, these procedures calculate the results using several alternative models and then select the best model depending on the value of R^2 and CV(RMSE). The simplest model can be calculated by statistically regressing average daily utility consumption data against billing period degree-days or average billing period temperatures.

Note: By using the average daily consumption (monthly consumption divided by reading period days), the regression procedure must use a weighted regression technique. This is described in more detail in Annex D.

There are several advantages to using single-variable linear type models, including the following:

- the application can be automated and applied to large numbers of buildings where monthly utility billing data and average daily temperatures are available,
- it has been shown that linear and change-point linear models have physical significance to the actual heat loss/gain mechanisms that govern the energy use in most buildings, and
- linear models are well understood and should yield results that are reproducible for independent cross-checking.

The model shall as a minimum meet the requirements in clause 5.3.2.1 and/or 5.3.2.2 for net determination bias and for CV(RMSE) if the prescriptive compliance path is chosen.

6.1.3.4 Calculate Energy Savings. Once the appropriate model has been chosen, then the methodology for calculating the energy savings is the following:

1. *Calculate the projected baseline energy use.* This energy use is the amount that would have been used if the retrofits had not occurred, given the current billing period, weather, and/or other independent variables. This is called the projected baseline and is determined by substituting the current billing period data into the baseline energy model equation.
2. *Calculate the energy savings.*

Savings = Projected baseline energy use (pre-retrofit) - Current energy use (post-retrofit)

$$E_{savings} = E_{projected} - E_{current}$$

6.1.3.5 Calculate Demand Savings.

1. *Calculate the projected baseline demand.* This demand is the amount that would have been used if the retrofits had not occurred, given the weather and/or other independent variables. This is called the projected baseline demand and is determined by substituting the current billing period data into the baseline demand model equation.
2. *Calculate the demand savings.*

Savings = Projected baseline demand (pre-retrofit) – Current demand (post-retrofit)

$$Demand_{savings} = Demand_{projected} - Demand_{current}$$

6.1.3.6 Baseline Adjustments. Frequently the situation will arise that changes to the structure, operation, or usage of the facility during the post-retrofit period will occur. Whenever possible, the method of calculating the effect of such modifications should be agreed upon before entering into a contract.

The most straightforward and least conflict-prone way to account for changes is to submeter the effect of any addition to the structure, operation, or usage of the facility, if possible. For example, an addition of a new wing in a facility should be accompanied by the installation of submeter(s) to monitor energy use and demand in the new wing. Henceforth, the post-retrofit data would simply be the total metered amount less the submetered quantities. Only where such submetering is too costly, impossible, or inappropriate should the methods suggested below be used.

A method of estimating the effect of owner modifications on the projected baseline is to include another term in the baseline model equation. Hence, the baseline model, Equation 6.1-1, becomes

$$E = C + B_1V_1 + B_2V_2 + B_3V_3 + \ A_1V_n + ... \qquad (6.1\text{-}2)$$

where

A_1 = coefficient of the independent variable for the adjustment,

V_n = independent variable for the adjustment.

In many cases the baseline adjustment will be dependent on one of the already existing independent variables. That is, V_n may represent outdoor temperature, degree-days, etc. In other cases, the independent variable may be a new term added to the equation. For example, if cooling were added to a building in the post-retrofit period, then the independent variable would be cooling degree-days or cooling season temperatures.

The process of determining the baseline adjustment is the following:

- A separate calculation or simulation of the effect of the modification must be performed. This will involve simple engineering calculations for the more straightforward modifications to detailed computer simulation models. For example, additional lighting would be a base load change that can be easily calculated, whereas an addition to the building may involve an hourly simulation of both the new and the old structures so as to determine the effect of this type of modification.
- The time dependency of modifications must be accounted for, both for changes that occurred during the baseline period as well as in the post-retrofit period. For example, if equipment is added to a building in the post-retrofit period, the projected baseline energy use should not incorporate the modification for periods before the equipment was added.

6.1.3.7 Sample Models. Table 6.1-1 summarizes the various models that can be used.

Frequently such models are conditional on the values of their variables or on the season. For example, the term in a driving variable such as degree-days may apply only for temperatures above or below a balance temperature or during a specified season. Moreover, the values of one or more coefficients may be valid only for a range in outdoor temperature and be replaced by a different set of values in an adjacent range of outdoor temperature. More detailed information regarding each model, including example graphs and the computational form to apply for uncertainty calculations, are included in Annex D.

6.1.4 Modeling and Uncertainty Analysis. For each of two paths in this approach, the baseline model CV(RMSE) will be required to demonstrate the uncertainty in the model. See clause 5.2.11.3. Further to this, the performance path must incorporate uncertainty calculations in the savings values as explained in clause 5.2.11.4. More details about uncertainty calculations and various linear regression models are described in Annex B and Annex D, respectively.

6.2 Retrofit Isolation Approach.

6.2.1 General Overview. The retrofit isolation approach is intended for retrofits where the end-use capacity, demand, or power level can be measured during the baseline period, and the energy use of the equipment or subsystem can be measured post-installation for a short-term period or continuously over time. The retrofit isolation approach can involve a continuous measurement of energy use both before and after the retrofit for the specific equipment or energy end-use affected by the retrofit or measurements for a limited period of time necessary to determine retrofit savings. Periodic inspections of the equipment may also be warranted. In most cases energy use is calculated by developing statistically representative models of the energy end-use capacity (e.g., the kW or Btu/h) and use (e.g., the kWh or Btu).

TABLE 6.1-1
Sample Models for Whole Building Approach

Name	Clause	Independent Variable(s)	Form	Examples
No Adjustment/ Constant Model	6.1.4.1	None	$E = E_b$	Non-weather-sensitive demand
Day Adjusted Model	6.1.4.2	None	$E = E_b \times \frac{day_b}{day_c}$	Non-weather-sensitive use (fuel in summer, electricity in summer)
Two-Parameter Model	6.1.4.3	Temperature	$E = C + B_1(T)$	
Three-Parameter Models	6.1.4.4	Degree-days/Temperature	$E = C + B_1(DD_{BT})$ $E = C + B_1(B_2 - T)^+$ $E = C + B_1(T - B_2)^+$	Seasonal weather-sensitive use (fuel in winter, electricity in summer for cooling) Seasonal weather-sensitive demand
Four-Parameter, Change Point Model	6.1.4.5	Temperature	$E = C + B_1(B_3 - T)^+ - B_2(T - B_3)^+$ $E = C - B_1(B_3 - T)^+ + B_2(T - B_3)^+$	
Five-Parameter Models	6.1.4.6	Degree-days/Temperature	$E = C - B_1(DD_{TH}) + B_2(DD_{TC})$ $E = C + B_1(B_3 - T)^+ + B_2(T - B_4)^+$	Heating and cooling supplied by same meter.
Multi-Variate Models	6.1.4.7	Degree-days/Temperature, other independent variables	Combination form	Energy use dependent, non-temperature-based variables (occupancy, production, etc.).

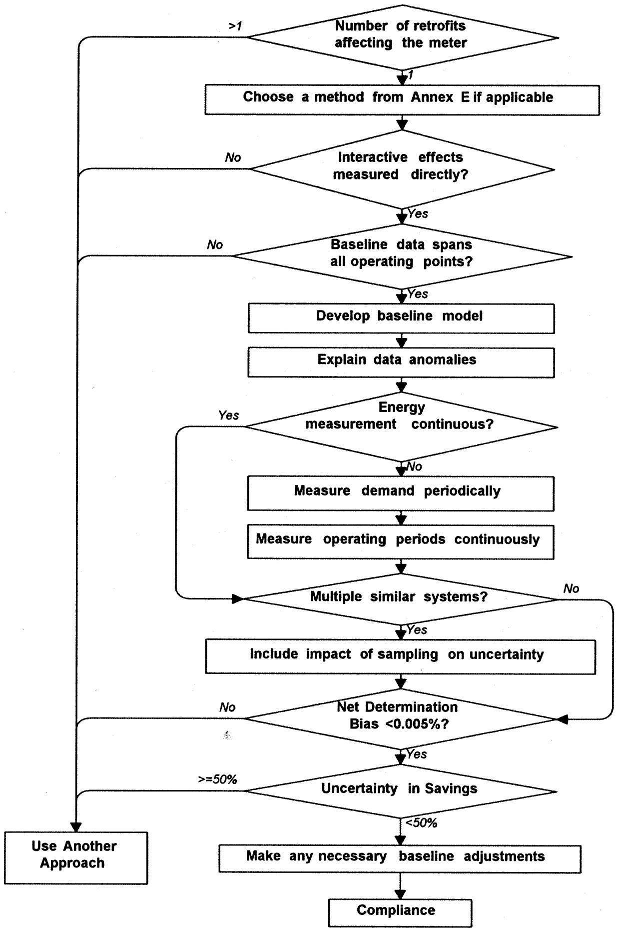

Figure 6.2-1 Flow chart for retrofit isolation approach performance path

6.2.1.1 When to Use Retrofit Isolation Approach. The retrofit isolation approach should be used when the whole building approach is not appropriate and the savings in question can be determined by measurements taken at a specific equipment item or subsystem.

The whole building approach may not be appropriate if the savings to be determined are relatively small or if there is an unrelated change in the building served by the meter. For example, a retrofit may involve replacing oversized pumps (that have to be throttled for proper balancing) with properly sized pumps and energy efficient motors. In this case, the relative magnitude of the savings is probably too small for the whole building approach. In another situation, a major cooling system retrofit may also be accompanied by other unrelated changes (e.g., conversion of a warehouse area into an office area served by an independent HVAC system, installation of more efficient outdoor lighting by the owner, etc.). Situations such as these would warrant consideration of the use of the retrofit isolation approach.

The retrofit isolation approach may also be appropriate when the total savings from several changes can be determining by taking measurements for a subsystem. For example, the cooling energy saved by retrofitting several air-handling units (AHUs) (economizers, conversion to VAV, etc.) in one wing of a large building could be determined by measurements taken at the chilled water riser serving the AHUs.

Other situations where the retrofit isolation approach can be used is when contractually only the performance of a specific equipment item is of interest or when the interactive effects of ECMs do not exist or can be ignored.

6.2.1.2 When Not to Use Retrofit Isolation Approach. There are several possible situations where the use of the retrofit isolation approach is not appropriate. Typically this approach is not appropriate for determining the individual savings from the implementation of several ECMs. It is also not appropriate when several ECMs have been implemented and their cumulative or interactive savings cannot be determined by measurements taken at one or two specific equipment items or subsystems.

6.2.1.3 Review of Previous Work. The retrofit isolation approach relies heavily upon the in-situ measurement of the energy used by a particular piece of equipment or system. There is a large body of standards related to HVAC equipment testing. Various organizations have developed standards for these measurements to facilitate consistency in research and industry applications and for reference within other standards. In particular, there are several standards for laboratory measurement of temperature, pressure, airflow, liquid flow, power, thermal energy, and the testing of chillers, fans, pumps, motors, boilers, and furnaces. Advice is also available in the literature regarding the in-situ measurement of lighting, thermal storage, and HVAC systems (airside). Such standards describe procedures for characterizing the equipment performance, executing the tests, and calculating performance indices. In addition, there are separate standards for performing the individual measurements. See Annex A3, Laboratory Standards for Measurement of Physical Characteristics, and Annex A4, Equipment Testing Standards.

6.2.2 Criteria for Approach. The application of the retrofit isolation approach involves the following steps:

1. Select independent variables and develop model
2. Select and document baseline conditions
3. Select duration and frequency of monitoring for baseline and post-retrofit periods
4. Project baseline usage to post-retrofit conditions
5. Determine savings by

Savings = Projected Baseline (usage, demand) – Post Retrofit (usage, demand)

The type of load and type of retrofit affects instrumentation and modeling requirements. Loads can be classified according to whether the load is fixed or variable or whether the use is constant or variable. This classification makes a distinction between constant or varying loads (i.e., different rates at which the system uses energy) versus constant or varying uses (i.e., different rates at which the system is used) primarily for purposes of measurement. This results in the following four classifications:

1. Constant load, constant use
2. Constant load, variable use
3. Variable load, constant use
4. Variable load, variable use

The kinds of retrofit isolation are characterized by the kind of load and schedule for the load before the retrofit and the effect that the retrofit has on the load and schedule. The load is either constant or variable and the schedule is either a known or an unknown/variable schedule. The retrofit may change the magnitude of the load and/or change it to/from a constant load from/to a variable load. The retrofit may also change the schedule.

The following clauses discuss the instrumentation and calculation requirements for various classifications.

6.2.3 Methodology and Calculation Steps.

6.2.3.1 Same Load Classification Before and After Retrofit. Clause 6.2.3 discusses the metering and calculation requirements for situations where the loads have the same classification before and after the retrofit. In these cases, the retrofit may affect the magnitude or the duration of a load.

6.2.3.1.1 Constant Load, Constant Use. Constant load, constant use systems consist of systems where the energy used by the system is constant (i.e., varies by less than 5%) and the use of the system is constant (i.e., varies by less than 5%) through both the baseline or post-retrofit period.

In such systems the savings from an energy conservation measure can be made using (a) one-time, end-use baseline energy use measurement and one-time, end-use post-retrofit energy use measurement; (b) one-time, end-use baseline energy use measurement and continuous end-use energy use measurement; (c) continuous, before-after end-use energy use measurement,

(a) *One-time, end-use baseline energy use measurement and one-time, end-use post-retrofit energy use measurement*, where savings are calculated by comparing the difference of the one-time, end-use baseline versus post-retrofit energy use measurement times the hours of operation in the post-retrofit period with the following equation:

$$KWH_{save} = (KW_{onetime,\ baseline} - KW_{onetime,\ post\text{-}retrofit}) \times Hours_{post\text{-}retrofit} \qquad (6.2\text{-}1)$$

where

KWH_{save} = electricity savings from the retrofit (kWh),

$KW_{onetime,\ baseline}$ = one-time, end-use watt-hour measurements made during the baseline period,

$KW_{onetime,\ post\text{-}retrofit}$ = one-time, end-use watt-hour measurements made during the post-retrofit period,

$Hours_{post\text{-}retrofit}$ = hours that the system is in use in the post-retrofit period.

(b) *One-time, end-use baseline energy use measurement and continuous end-use energy use measurement*, where savings are calculated by comparing the difference of the one-time end-use baseline times the hours of operation versus continuous post-retrofit energy use measurement with the following equation:

$$KWH_{save} = (KW_{onetime,\ baseline}) \times Hours_{post\text{-}retrofit} - (KWH_{continuous,\ post\text{-}retrofit}) \qquad (6.2\text{-}2)$$

where

KWH_{save} = electricity savings from the retrofit (kWh),

$KW_{onetime,\ baseline}$ = one-time, end-use watt-hour measurements made during the baseline period,

$KWH_{continuous,\ post\text{-}retrofit}$ = continuous end-use watt-hour measurements made during the post-retrofit period,

$Hours_{post\text{-}retrofit}$ = hours that the system is in use in the post-retrofit period.

(c) *Continuous, before-after end-use energy use measurement*, where savings are calculated by comparing the difference of the continuous end-use baseline versus continuous post-retrofit energy use measurement with the following equation:

$$KWH_{save} = (KWH_{continuous,\ baseline}) - (KWH_{continuous,\ post\text{-}retrofit}) \qquad (6.2\text{-}3)$$

where

KWH_{save} = electricity savings from the retrofit (kWh),

$KWH_{continuous,\ baseline}$ = continuous end-use watt-hour measurements made during the baseline period,

$KWH_{continuous,\ post\text{-}retrofit}$ = continuous end-use watt-hour measurements made during the post-retrofit period.

6.2.3.1.2 Constant Load, Variable Use. Constant load, variable use systems consist of systems where the energy used by the system is constant (i.e., varies by less than 5%) but the use of the system is variable (i.e., varies by more than 5%) through either the baseline or post-retrofit period.

In such systems the savings from an energy conservation measure can be made using (a) one-time, end-use baseline energy use measurement and continuous end-use energy use measurement and (b) continuous, before-after end-use energy use measurement as defined in 6.2.4.1 above.

6.2.3.1.3 Variable Load, Constant Use. Variable load, constant use systems consist of systems where the energy used by the system is variable (i.e., varies by more than 5%) but the use of the system is constant (i.e., varies by less than 5%) through either the baseline or post-retrofit period.

In such systems the savings from an energy conservation measure can be made using:

a. *Continuous, before-after end-use energy use measurement* as defined in 6.2.4.1 above for those cases where the variation in the use is due to unpredictable schedule effects.

b. *Continuous before-after end-use energy use measurement* where a statistical model is created of the baseline use and is used to forecast the baseline use into the post-retrofit period. Energy use is then calculated by comparing the forecasted baseline use against the actual post-retrofit end-use energy use as follows:

$$E_{save,i} = E_{baseline,i} - E_{post\text{-}retrofit,i} \quad (6.2\text{-}4)$$

where

$E_{save,i}$ = energy savings from the energy conservation measure for period (i),

$E_{baseline,i}$ = the baseline energy use projected into the post-retrofit period by multiplying the statistical baseline models' parameters by the influencing variables from the post-retrofit period,

$E_{post\text{-}retrofit,i}$ = the actual post-installation energy use during period (i).

6.2.3.1.4 Variable Load, Variable Use. Variable load, variable use systems consist of systems where the energy used by the system is variable (i.e., varies by more than 5%) and the use of the system is variable (i.e., varies by more than 5%) through either the baseline or post-retrofit period.

In such systems the savings from an energy conservation measure can be made using:

a. *Continuous, before-after end-use energy use measurement* as defined in 6.2.4.1 above for those cases where the variation in the use is due to unpredictable schedule effects.

b. *Continuous before-after end-use energy use measurement* where a statistical model is created of the baseline use and is used to forecast the baseline use into the post-retrofit period. Energy use is then calculated by comparing the forecasted baseline use against the actual post-retrofit end use energy use as follows:

$$E_{save,i} = E_{baseline,i} - E_{post\text{-}retrofit,i}) \quad (6.2\text{-}5)$$

where

$E_{save,i}$ = energy savings from the energy conservation measure for period (i).

$E_{baseline,i}$ = the baseline energy use projected into the post-retrofit period by multiplying the statistical baseline model's parameters by the influencing variables from the post-retrofit period. $E_{baseline,i}$ must also take into account the varying hour of operation in the post-retrofit period.

$E_{post\text{-}retrofit,i}$ = the actual post-installation energy use during period (i).

6.2.3.2 Different Load Classifications Before and After Retrofit. A retrofit may change the magnitude of the load and/or change it to/from a constant load from/to a variable load. The retrofit may also change the schedule.

For conversion of a constant load to a varying load, such as photocell dimming controls installed on manually controlled indoor light fixtures, it is necessary to measure pre-installation kW and install a kWh meter and run-time meter on the line side of the dimmer. Savings are calculated by multiplying the measured circuit full-load kW by the operating hours from the run-time meter minus the kWh measured at the dimmer.

For variable load changed to higher efficiency variable load, such as converting a VAV system using inlet vanes to a variable speed drive on the fan motors, an energy-indexing method can be employed. This is done by measuring pre-installation kW of the fan at several flow rates to determine the baseline power flow relationship. After installation, measure the variable speed drive power and flow rates to determine the new power/flow relationship. By recording the flow rates for a representative post-retrofit period, the savings are calculated as a function of flow by the differences in the kW/CFM values times the hours of flow at representative flow levels.

There are numerous possible combinations of before and after retrofit load classifications. Table 6.2-1 summarizes the possible combinations and lists the metering requirements for each combination.

Load:

a. Constant (CL)—it must be known that under no circumstances could the load (kW or kVA) have varied by more than ±5% for that full year of operation or some other percentage considered acceptable to the client. In order for the client to decide if the percent variation is sufficiently close to constant, the worst case effect of this approximation should be expressed to them in both billing determinants (kWh and kVA or kW) and in dollars ($) over the year so that they can make an informed decision. Loads with a predictable use profile that results in constant energy use over a known period (work week, weekend, etc.) can be treated as constant loads.

b. Variable (VL).

Schedule:

a. Known timed on/off schedule (TS) should be set so the total hours of operation can be calculated based on the scheduled settings (i.e., without any runtime measurements), for example, controlled by a time clock or EMCS or always on. If the load is constant for either the pre-retrofit and post-retrofit cases and demand savings are to be calculated, the schedule has to be detailed enough to know exactly when the load was on or off in order to determine the coincident demand. If this is not possible, the schedule must be considered variable for that particular time period (pre- or post-retrofit).

b. Unknown/variable schedule (VS), such as if randomly turned on/off, controlled by occupancy sensor or temperature, or on timeclock but often manually overridden.

Terms in Table 6.2-1 are defined as follows:

One-time load measurement: Load has to have been measured at least once, more if necessary, to prove that load is a "constant" load, i.e., does not vary by more than ±5%. Load is measured in the units corresponding to the billing determinants, e.g., kW and, if necessary, kVA. If one-time load measurement and sufficient measurement of runtime are required, these could be replaced by "sufficient load measurement to characterize load" as defined below.

Sufficient measurement of runtime: Continuous measurement of runtime unless it can be shown that sufficient data have been measured in that year to predict what the runtime would have been for that full year of operation.

Sufficient load measurements to characterize the load: Continuous measurement of the load unless it can be shown that sufficient data have been measured in that year to predict what the energy use and coincident demand would have been for that full year of operation. If the pre-retrofit load is variable, one needs to have sufficient information on what controls the variation in the load before the retrofit to develop a model to predict what the energy use and coincident demand would have been had the retrofit not taken place. This also would require sufficient information for the post-retrofit period to apply the model for that time period.

6.2.3.4 Data Characteristics. As outlined in Table 6.2-1, the data requirements will vary from one-time load measurements to measurements that are sufficient to characterize loads. The resulting data can range from single measurements (or a few measurements to establish that load and use are constant) to continuous measurements (subhourly/hourly) over the full range of independent variables to sufficiently characterize loads and operating periods.

The whole building approach often relies on utility grade meters to measure energy use and demand where measurement uncertainty can be ignored. Retrofit isolation measurement protocols can utilize a wide range of field-installed measuring instruments and the uncertainty of the measured data can vary over a wide range. The energy use and demand of a lighting circuit or a chiller can be measured with little uncertainty. In contrast, the measurement uncertainty of the charging rate of a thermal storage system can be significant.

The retrofit isolation approach can also result in large amounts of subhourly/hourly data. While this can improve the accuracy of the baseline model, care must be taken to avoid the development of an unnecessarily complex model where simpler models may be adequate.

6.2.4 Modeling and Uncertainty Analysis. A statistical model of the baseline energy use must be developed to relate the energy/demand in terms of one or more independent variables. The most common independent variable is the outdoor temperature. Annex D discusses regression techniques and describes several models that can be developed. Clause 6.1.4 discusses several models that are applicable for the whole building approach. In general, these models are also valid for the retrofit isolation approach.

Depending on the chosen model and the measurement techniques, data may be available in the form of a few readings, discrete readings at intervals of time, or continuous data. The simplest model that meets the desired objectives should be used. As discussed in Annex D, the number of independent variables can be reduced by examining the physical parameters and including only those that are independent and have physical causality. A clear benefit may be had by separating the data into different regimes of behavior, for example, heating/cooling season, weekday/weekend, etc. Even where subhourly/hourly data are available, weekly or daily analysis with separate weekday/weekend models will provide the best results for most buildings. Hourly analysis may be needed for some buildings with unusual energy usage characteristics, such as strong on/off effects.

Clause 5 states the compliance requirements for the retrofit isolation approach. These include the requirement to perform an uncertainty analysis showing a net determination bias of less than 0.005% and a reporting of the maximum level of uncertainty, which must be less than 50% of the reported savings with 68% confidence. The contracting parties may choose to require a lower level of uncertainty at a higher confidence level.

The overall uncertainty for the retrofit isolation approach will be the sum of:

1. Modeling uncertainty
2. Measurement uncertainty

Since the modeling involves the characterization of specific loads in terms of independent variables, the modeling uncertainty will generally be low in comparison to the whole building approach. Depending on the specific measurements being taken, the measurement uncertainty can be significantly higher. The fractional uncertainty is expressed by Equation (6.2-6):

$$\frac{\Delta\sum E_{save}}{\sum E_{save}} = t \cdot \frac{[\Delta(\sum E_{pre})^2 + \Delta(m \cdot \bar{E}_{meas})^2]^{1/2}}{m \cdot \bar{E}_{pre} F} \qquad (6.2\text{-}6)$$

This equation can be simplified for situations where the measurement uncertainty is low, as would be the case for lighting or chiller use and demand measurements.

Annex B contains a general discussion on uncertainty and its determination. It presents examples of simplified equations for different situations where measurement uncertainty can be ignored. Example equations are provided for (equation numbers refer to numbers in Annex B):

- Energy uses independent of weather and other variables (e.g., lighting retrofits)—Equation (B-10).
- Monthly energy use data varying in response to known independent variables (e.g., weather)—Equation (B-13a).
- Daily or hourly energy use data varying in response to known independent variables—Equation (B-15).

See Annex E for a detailed description of retrofit isolation approach techniques by system.

6.2.5 Bibliography

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TABLE 6.2-1
Retrofit Isolation Applications and Metering Required to Calculate Energy and Demand Savings

Pre-Retrofit	Retrofit Changes	Required Metering: Pre-Retrofit	Required Metering: Post-Retrofit
CL/TS	Load but still CL	One-time load msmt	One-time load msmt
CL/TS	Load to VL	One-time load msmt	Sufficient load msmts to characterize load
CL/TS	Schedule but still TS	One-time load msmt (either pre- or post-retrofit)	
CL/TS	Schedule to VS	One-time load msmt (either pre- or post-retrofit)	Sufficient msmt of runtime
CL/TS	Load but still CL and schedule but still TS	One-time load msmt	One-time load msmt
CL/TS	Load to VL and schedule but still TS	One-time load msmt	Sufficient load msmts to characterize load
CL/TS	Load but still CL and schedule to VS	One-time load msmt	One-time load msmt and sufficient msmt of runtime
CL/TS	Load to VL and schedule to VS	One-time load msmt	Sufficient load msmts to characterize load
CL/VS	Load but still CL	One-time load msmt and sufficient msmt of runtime	One-time load msmt and sufficient msmt of runtime
CL/VS	Load to VL	One-time load msmt and sufficient msmt of runtime	Sufficient load msmts to characterize load
CL/VS	Schedule to TS	One-time load msmt (either pre- or post-retrofit) and sufficient msmt of runtime	
CL/VS	Schedule but still VS	One-time load msmt (either pre- or post-retrofit) and sufficient msmt of runtime	Sufficient msmt of runtime
CL/VS	Load but still CL and schedule to TS	One-time load msmt and sufficient msmt of runtime	One-time load msmt
CL/VS	Load to VL and schedule but still TS	One-time load msmt and sufficient msmt of runtime	Sufficient load msmts to characterize load
CL/VS	Load but still CL and schedule to VS	One-time load msmt and sufficient msmt of runtime	One-time load msmt and sufficient msmt of runtime
CL/VS	Load to VL and schedule but still VS	One-time load msmt and sufficient msmt of runtime	Sufficient load msmts to characterize load
VL/TS or VS	Load to CL	Sufficient load msmts to characterize load	One-time load msmt and sufficient msmt of runtime
VL/TS or VS	Load but still VL	Sufficient load msmts to characterize load	Sufficient load msmts to characterize load
VL/TS or VS	Schedule still or to TS	Sufficient load msmts to characterize load	Sufficient load msmts to characterize load
VL/TS or VS	Schedule to or still VS	Sufficient load msmts to characterize load	Sufficient load msmts to characterize load
VL/TS or VS	Load to CL and schedule still or to TS	Sufficient load msmts to characterize load	One-time load msmt
VL/TS or VS	Load but still VL and schedule still or to TS	Sufficient load msmts to characterize load	Sufficient load msmts to characterize load
VL/TS or VS	Load to CL and schedule to or still VS	Sufficient load msmts to characterize load	One-time load msmt and sufficient msmt of runtime
VL/TS or VS	Load but still VL and schedule to or still VS	Sufficient load msmts to characterize load	Sufficient load msmts to characterize load

CL = constant load
msmt = measurements
TS = timed (known) schedule
VL = variable load
VS = variable (unknown) schedule

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6.3 Whole Building Calibrated Simulation Approach (Calibrated Simulation)

6.3.1 General Overview. This clause refers to computer-based simulation of whole building energy use behavior. This technique is especially applicable to accounting for multiple energy end-uses, especially where interactions occur between measures. Additionally, this technique is useful for situations where baseline shifts may be encountered and where future energy impacts may need to be accessed.

6.3.1.1 Hourly Simulation Programs. Of the hourly simulation programs available, there is one category that is not suitable for the techniques described in this clause: programs that utilize average weather days. Unlike the major hourly simulation programs that accept hourly weather files containing data for 8760 hours, these other programs contain an average weather day and a peak weather day for each month. The average weather day programs simulate building energy processes for these few average days and extrapolate the results to represent annual energy performance. Average weather day programs cannot accept weather data from specific time periods and, as such, are not appropriate for calibration purposes.

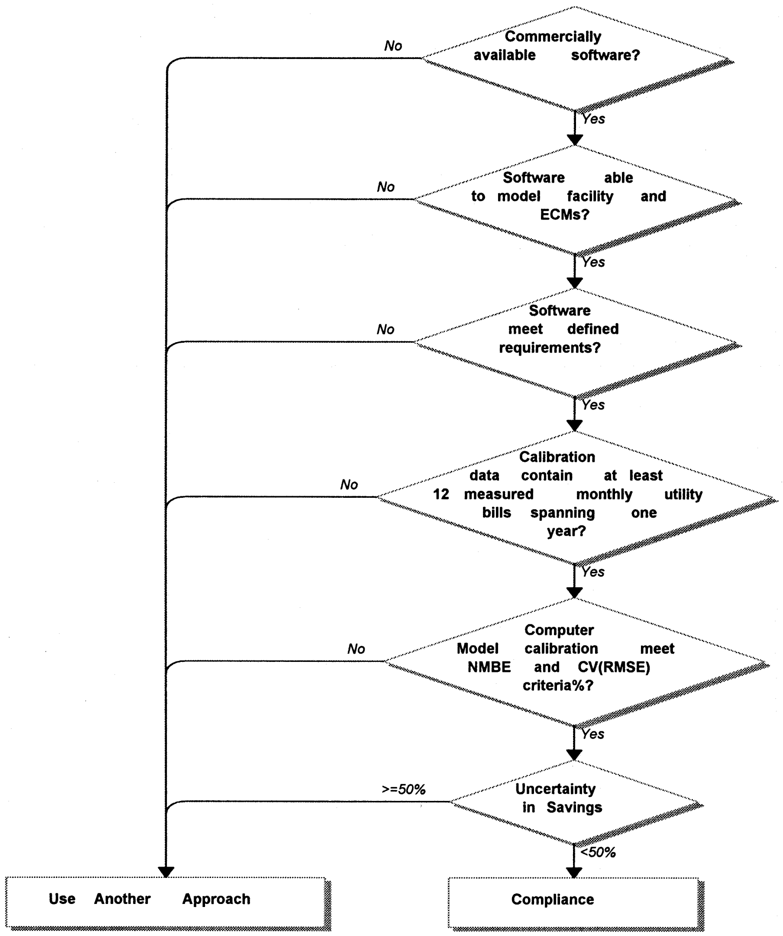

Figure 6.3-1 Flow chart for whole building calibrated simulation performance path.

6.3.1.2 Compliance. Use of this technique shall conform to the requirements outlined in clause 5.3, Compliance Requirements, including clause 5.3.2.4.

6.3.2 Criteria for Calibrated Simulation.

6.3.2.1 When to Use Calibrated Simulation. Calibrated simulation is an appropriate method to consider when one or more of the following conditions are present:

1. *Either pre-retrofit or post-retrofit whole-building metered electrical data are not available.* The building may either be a new building or there may be new equipment to meter whole-building energy usage and demand was not installed until after the retrofit.

2. *Savings cannot be easily determined using before-after measurements.* For example, savings achieved by modifying HVAC equipment are strongly influenced by weather. Simply taking before and after measurements would not necessarily yield an accurate representation of savings. By using calibrated simulation, savings can be "normalized" to represent the savings that would have been achieved over the course of a pre-determined weather year at specific equipment settings. Typical weather year files are available for such analyses.

3. *Measures interact with other building systems, and it is desired to account for those interactions, and retrofit isolation methods are not readily feasible.* When lighting systems are improved in air-conditioned buildings, for example, less heat emitted from the lighting systems need be removed by the air-conditioning system. During the heating season, however, that saved lighting heat will add a burden to the building heating system. Building simulation is capable of accounting for these interactive energy flows if the HVAC systems are appropriately modeled.

4. *Only whole-building energy use data are available but savings from individual retrofits are desired.* When building simulations are calibrated to whole-building data, information regarding energy flows among individual retrofits and other building changes can be discerned by the simulation model.

5. *Baseline adjustment needs.* In situations where significant changes in the facility's energy use and demand occur over time, and these changes are not related to the energy conservation measures, adjustments to account for these changes will be needed. Changes of this nature, especially those involving multiple factors, can readily be addressed using simulation. Examples might include cases where weather patterns, changes in hours of operation, and the addition of new uses simultaneously impact the facility.

Calibrated simulation should also be considered where a number of the above conditions exist that can all be addressed through the use of simulation. Finally, calibrated simulation is quite useful where future work in the facility would benefit from the availability of a model to explore potential changes as well as adjust for their impacts.

6.3.2.2 When Not to Use Calibrated Simulation Method. The calibrated simulation method is not recommended when any of the following five conditions are evident:

1. *Measures that can be analyzed without building simulation.* The use of calibrated simulation is NOT recommended if less expensive methods produce similar results. For example, end-uses that do not impact HVAC energy use may be much more economically analyzed using spot measurements, hand calculations, or computer spreadsheets. Measures that fall into this category include outdoor lighting retrofits, some motor replacements, elevator machinery improvements, and domestic water heater replacements.
2. *Buildings that cannot be readily simulated.* Most building types can be simulated. However, buildings that may not be easily simulated with commonly available programs include (a) buildings with large atriums where internal temperature stratification is significant and thermal convection is an important feature of the heating or cooling system, (b) buildings that are underground, (c) buildings with unusual exterior shapes or extremely complex shading configurations, and (d) buildings with continual and/or poorly defined load changes other than energy-conserving measures.
3. *HVAC systems that cannot be simulated.* Most commonly available HVAC systems can be simulated with today's public domain simulation programs. However, certain control options that are in use in existing buildings are extremely difficult to reproduce with a simulation program, especially local control options in large buildings that have a large number of HVAC systems since many simulation programs are limited to the number of zones that they can simulate.
4. *Retrofits that cannot be simulated.* For example, savings from the addition of radiant barriers in an attic or changes to certain HVAC control settings that are outside of the allowable settings in many of today's programs or require expensive modifications to an existing code.
5. *Project resources are not sufficient to support calibrated simulation.* Before committing to the calibrated simulation method, ensure that a model of the building can be created, calibrated, and documented within the project's time frame and budget constraints.

6.3.3 Methodology and Calculation Steps. When employing calibrated simulation to estimate the savings associated with energy conservation measures, follow the procedure summarized below and detailed in clauses 6.3.3.1 through 6.3.3.8.

1. *Produce a calibrated simulation plan.* Before a calibrated simulation analysis may begin, several questions must be answered. Some of these questions include: Which software package will be applied? Will models be calibrated to monthly or hourly measured data, or both? What are to be the tolerances for the statistical indices? The answers to these questions are documented in a simulation plan. See clause 6.3.3.1.
2. *Collect data.* Data may be collected from the building during the baseline period, the retrofit period, or both. Data collected during this step include dimensions and properties of building surfaces, monthly and hourly whole-building utility data, nameplate data from HVAC and other building system components, operating schedules, spot-measurements of selected HVAC and other building system components, and weather data. See clause 6.3.3.2.
3. *Input data into simulation software and run model.* Over the course of this step, the data collected in the previous step are processed to produce a simulation-input file. Modelers are advised to take care with zoning, schedules, HVAC systems, model debugging (searching for and eliminating any malfunctioning or erroneous code), and weather data. See clause 6.3.3.3.
4. *Compare simulation model output to measured data.* The approach for this comparison varies depending on the resolution of the measured data. At a minimum, the energy flows projected by the simulation model are compared to monthly utility bills and spot measurements. At best, the two data sets are compared on an hourly basis. Both graphical and statistical means may be used to make this comparison. See clause 6.3.3.4.
5. *Refine model until an acceptable calibration is achieved.* Typically, the initial comparison does not yield a match within the desired tolerance. In such a case, the modeler studies the anomalies between the two data sets and makes logical changes to the model to better match the measured data. The user should calibrate to both pre- and post-retrofit data wherever possible and should only calibrate to post-retrofit data alone when both data sets are absolutely unavailable. While the graphical methods are useful to assist in this process, the ultimate determination of acceptable calibration will be the statistical method. See clause 6.3.3.5.
6. *Produce baseline and post-retrofit models.* The baseline model represents the building as it would have existed in the absence of the energy conservation measures. The retrofit model represents the building after the energy conservation measures are installed. How these models are developed from the calibrated model depends on whether a simulation model was calibrated to data collected before the conservation measures were installed, after the conservation measures were installed, or both times. Furthermore, the only differences between the baseline and post-retrofit models must be limited to the measures only. All other factors, including weather and occupancy, must be uniform between the two models unless a specific difference has been observed that must be accounted for. See clause 6.3.3.6.
7. *Estimate Savings.* Savings are determined by calculating the difference in energy flows and intensities of the baseline

and post-retrofit models using the appropriate weather file. See clause 6.3.3.7.

8. *Report observations and savings.* Savings estimates and observations are documented in a reviewable format. Additionally, sufficient model development and calibration documentation shall be provided to allow for accurate recreation of the baseline and post-retrofit models by informed parties, including input and weather files. See clause 6.3.3.8.

The following clauses of this guideline describe each of these steps in detail.

6.3.3.1 Produce a Calibrated Simulation Plan. Prepare a simulation plan that addresses the following items:

1. *The baseline scenario.* The baseline scenario represents the building as it would exist in the absence of any energy conservation measures (refer to measurement plans in clause 5.3). For example, if the building is under construction, the baseline scenario represents the building as it would have been built without any energy-conservation measures. If the building is an existing building, the baseline is usually the building as it existed before the energy conservation measures. In the event changes are planned for the building that would have been implemented whether or not any conservation measures were undertaken, the baseline scenario represents the existing building with those planned changes.
2. *The post-retrofit scenario.* The measure scenario represents the building after the energy conservation measures are implemented. Document both the measures and their energy conservation characteristics.
3. *The simulation software package.* Full 8760 hourly simulation programs shall be used (see clause 5.3.2.4). Document in the plan the name of the simulation software package that will be employed as well as the version number.
4. *Calibration to monthly or hourly data.* Monthly data are readily available and calibrations to such data are less time consuming than calibrations to hourly data. Calibrations to hourly data are more accurate but also more difficult and expensive. In either case, at least 12 continuous months of whole building energy use and demand data in at least 12 valid meter readings are required, along with hourly weather data corresponding to the same period as the utility data. Document in the plan the planned interval of the measured data (e.g., monthly or hourly).
5. *Tolerances for statistical calibration indices.* Graphical calibration parameters as well as two main statistical calibration indices (mean bias error and coefficient of variation (root mean square error)) are described in clause 6.3.3.4.2.2. Document the acceptable limits for these indices on a monthly and annual basis.
6. *Spot and short-term measurements of building system characteristics.* Even though a reasonable match is developed between the modeled and measured energy flows, it's not certain that the model is a good representation of the actual building. There remains the possibility that there are offsetting internal errors in the model. By taking spot and short-term measurements of building system characteristics, the likelihood that significant offsetting errors exist can be reduced, but these measurements add cost to the calibrated simulation effort. Such measurements are described in clause 6.3.3.2.6 below. Describe in the simulation plan guidelines for selecting and implementing spot and short-term measurements.

6.3.3.2 Collect Data. Over the course of this step, the data required to support the remainder of the analysis are collected. These data may be collected before the conservation measures are installed, after the conservation measures are installed, or at both times. The methods to be followed are described in the following clauses.

6.3.3.2.1 Obtain Building Plans. As-built plans are preferable, but collect whatever plans are available. When on site, confirm that building geometry and construction materials represented in the plans are accurate. Photograph the building exterior and its surroundings to document architectural and shading features such as trees, etc.

6.3.3.2.2 Collect and Review Utility Data.

1. At a minimum, collect utility bills spanning at least one year composed of at least 12 valid meter readings, including monthly electricity use, peak electric demand for the month, and monthly fuel use for heating (e.g., natural gas, fuel oil, etc.). If electric demand data are available, identify the type of demand data (e.g., sliding window or fixed window) and the integration period (e.g., 15-, 30-, or 60-minute data), since there may be significant differences between the actual electric peak demand and the hourly peak demand reported by the simulation program. Collect bills from submeters if they are installed, and obtain information regarding the dates meter readings were taken.
2. Obtain hourly (or smaller interval data) electric meter data if available from the utility.
3. If hourly data are not available from the utility but are required to calibrate the simulation model, install equipment to collect such data. Hourly data metering capabilities may be integrated into the utility meter, built into the electrical switchgear, or provided by add-on watt transducers. Most electric meters that collect interval data may be interrogated by modem, linked to an energy management system, or added onto an electronic network. Sometimes this service is available from the electric utility for a small charge.

6.3.3.2.3 Prepare for Data Collection as Defined in the Simulation Plan. Develop data collection forms to document and archive use, thermostat setting, occupancy, and operational data as defined in the simulation plan.

6.3.3.2.4 Conduct On-Site Surveys. Visit the site and collect data by making visual observations of in-situ building system components. The specific data to collect vary widely depending upon the desired tolerances of the calibration and the individual building characteristics and, as such, cannot simply be proscribed here. Instead, the determination of which data to collect is left to the modeler and any agreements between buyer and seller. Data that may be collected during a site survey include:

1. *Lighting systems:* fixture counts, fixture types, nameplate data from lamps and ballasts, 24-hour weekday, weekend, and holiday schedule of lighting use indoors and outdoors, characteristics of fixtures for estimating radiative and connective heat flows, thermal zone assignments, and diversity of operation.
2. *Plug loads:* counts of and nameplate data from plug-in devices, 24-hour weekday and weekend usage schedules, and diversity of operation.
3. *HVAC systems:* quantities, capacities, and operating characteristics of primary equipment (e.g., chillers and boilers), part-load performance curves for primary equipment (efficiency vs. load), quantities and characteristics of secondary equipment (e.g., air-handling units, terminal boxes), fan sizes and types (e.g., forward curved, backward curved), motor sizes and efficiencies, determination whether motors are located in conditioned space, design flow rates and static pressures, types of duct systems (e.g., dual-duct constant volume and variable air volume), system zoning, interior zone temperature setpoints, control setpoints and schedules (e.g., cold deck temperature, hot deck temperature, and economizer setpoint), air flow control types (discharge damper, inlet vanes, VSD), coil characteristics including sensible heating factor, condenser characteristics and controls, temperatures of the air leaving the heating and cooling coils, characteristics of supply and return ducting, and functionality of economizers and other major components.
4. *Building envelope and thermal mass:* dimensions and thermal resistance of external and interzonal surfaces, orientation of external surfaces, thermal mass characteristics of materials of construction, dimensions, visible and infrared transmittance of external transparent surfaces (windows, doors, and skylights), spacing of framing materials, and shading from nearby objects.
5. *Building occupants:* population counts, weekday, weekend, and holiday schedules, activity levels, and assignments to thermal zones.
6. *Other major energy-using loads:* identification of special loads (industrial process, air compressors, water heaters, vertical transportation), energy use, schedules of operation.

6.3.3.2.5 Interview Operators and Occupants. Confirm schedules of occupancy and operation. Identify any operating problems/special conditions that must be replicated by the calibrated model.

6.3.3.2.6 Conduct Spot and Short-Term Measurements. These measurements include spot measurements, which are taken for a moment, usually using hand-held instruments, or short-term measurements, for which instruments with data logging capabilities are set up and left in place to collect data for longer periods of time. Spot measurements are less expensive, but short-term measurements provide valuable information regarding schedules of use. The appropriate measurements to make as well as their duration vary widely depending upon the desired accuracy of the calibration and the individual building characteristics and, as such, cannot simply be proscribed here. Instead, the determination of which measurements to take is left to the modeler and any agreements between buyer and seller. Such in-situ measurements may include:

1. *Lighting systems:* operating schedules, fixture power.
2. *Plug loads:* operating schedules, electric power.
3. *HVAC systems:* space temperatures and humidities, air and water flows, static pressures and temperatures, motor power, duct leakage.
4. *Building ventilation and infiltration:* air flows through outside air ducts, building pressurization or tracer gas tests of infiltration rates (if infiltration is expected to be an important issue).
5. *Other major energy-using loads:* energy use, operating schedules.

6.3.3.2.7 Collect Weather Data. Two different kinds of weather data may be required to estimate savings using calibrated simulation. At a minimum, the modeler collects hourly weather data that corresponds to the same time period as the energy use data to which the model will be calibrated. If the savings are to be "normalized" to represent a typical year, the modeler also collects typical year weather data using a site that is near to the facility (usually an airport).

Weather data that correspond to a specific time period may be collected either from an on-site station or from the National Climatic Data Center (NCDC), which maintains records from hundreds of sites in the U.S. and around the world.* Although NCDC data are available in most of the formats accepted by simulation programs, most specific time period data sets do not include solar radiation data. Most hourly simulation programs, however, include modules that can synthesize solar radiation from the cloudiness values in the NCDC data.

If average hourly weather data is to be used to project typical year savings (as opposed to a specific year's), it can be obtained from ASHRAE (WYEC2), the National Climatic Data Center (TMY), and the National Renewable Energy Laboratory (TMY2). TRY weather data files, which are available from the National Climatic Data Center, are not recommended for this purpose (Huang and Crawley 1996).

Although some modelers have reported using average or typical year weather data for model calibration, this approach is not recommended since the comparison utility data will have been incurred with actual weather from the time in question. Several studies have shown that using an average year weather file in a simulation can induce error into the simulation that is as large as some of the differences that are being sought in the analysis (Haberl et al. 1995, Huang and Crawley 1996).

6.3.3.3 Input Data into Simulation Software and Run Model. The best guide for inputting data into a model is the manual that accompanies the simulation software package. When preparing the simulation input data and doing preliminary runs, special attention should be paid to the issues discussed in 6.3.3.3.1-9.

6.3.3.3.1 Architectural Rendering. Several software programs have recently become available for purposes of architectural rendering or viewing of building simulation

* National Climatic Data Center is located at 151 Patton Ave., Federal Building, Asheville, NC 28801; 828-271-4800; www.ncdc.noaa.gov.

input files (Degelman 1995; Hirsch et al. 1995; Huang 1993). This software can be used to help ensure that building input parameters are consistent with the actual facility.

6.3.3.3.2 Accounting for Luminaire Temperatures. When estimating fluorescent ballast input power from nameplate ratings, it's important to account for thermal effects on lamps and ballasts. When the air temperature surrounding lamps driven by electronic ballasts is above or below about 77°F, ballast power will typically decrease below rated maximum input. A similar decrease is also observed when magnetic ballasts are present and air temperatures are above about 65°F. To estimate input power for a variety of combinations of ballasts, lamps, and luminaires, consult tables published in Bleeker and Veenstra (1990).

6.3.3.3.3 Estimating Plug Loads Based on Nameplate Ratings. Although measurements are preferable, plug loads may be estimated by taking inventory and summing up connected loads. When doing so, do not enter the nameplate power into the simulation software. On average, most plug load devices operate at an average power much lower than the nameplate rating. To estimate actual operating power, nameplate power is multiplied by a usage factor. A common rule of thumb for usage factor is 0.3. Note that there are a number of publications reporting actual load of computers and office equipment.

6.3.3.3.4 Converting Lighting and Receptacle Loads into Simulation Program Inputs. Since some programs also require information about the heat gain characteristic of each lighting fixture, attention should be paid to this input. Usually, determining the heat gain multiplier requires that the modeler identify the extent to which the lighting fixture is in thermal communication with unconditioned spaces and return air plenums.

6.3.3.3.5 HVAC System Zoning. The most important aspect to duplicate when zoning the simulated HVAC system is the on/off characteristic of a zone. Testing of the zoning assumptions in a simulation program usually requires simulating the building with actual hourly weather data, as well as hourly recordings of interior zone temperature, to compare against the simulated temperatures.

In large internal-load-dominated buildings, proper zoning can often be accomplished with as few as 15 "thermodynamic zones," including 5 zones on the uppermost floor, 5 zones on the ground floor, and 5 zones for the intervening floors.

6.3.3.3.6 HVAC System Simulation. In many cases, especially in simulation programs that use predetermined systems, it may not be possible to exactly simulate a building's HVAC system. In such cases the modeler is cautioned to make sure that the operating conditions of the HVAC system are being met by the simulation program, even though the schematic diagram may be different from the system being modeled.

6.3.3.3.7 Estimating Infiltration Rates. Infiltration rates are difficult to measure and may be treated as an unknown that is iteratively solved for with the simulation program once the other major parameters are determined. This approach is only recommended as a last resort. To solve for the infiltration rate and/or the ventilation rate iteratively, conduct a series of simulation runs such that the infiltration and/or ventilation rates range from 1/10 to as much as 10× the expected rates. Compare the simulation outputs so produced to the measured building data as discussed below. In addition, supporting evidence should be used to justify the final choice of variables.

6.3.3.3.8 Minimizing Default Values. Check and thoroughly understand all "default" input variables in the simulation program, since many of the default values have little resemblance to the actual building being simulated. The fewer the number of default values employed, the more representative will be the simulation but only if the changes are well reasoned. Any program default values that are altered, however, should be well documented.

6.3.3.3.9 Debugging Models. The amount of simulation iterations in the later steps can be minimized by thoroughly examining the simulation inputs and outputs to identify and eliminate input errors, or debugging. Kaplan et al. (1992) recommend the following checks as a minimum:

1. *Simulation input checks:* building orientation, zoning, external surface characteristics (orientation, area, zone assignment, thermal resistance, shading coefficient), lighting and plug load power densities, operating schedules, HVAC system characteristics (CFM, input power, zones served, minimum outside percentages, system types, heating and cooling capacities, fan schedules), plant equipment characteristics (type, capacities, rated efficiency, part-load efficiencies).
2. *Simulation output checks:*
   a. HVAC systems satisfy heating and cooling loads.
   b. Lighting and equipment schedules are appropriate.
   c. Fan schedules are appropriate.
   d. Ventilation air loads are appropriate.
   e. HVAC plant efficiencies are appropriate.

6.3.3.4 Calibration of Simulation Model Outputs to Measured Data. After inputting data into the simulation model and debugging the model, compare the energy flows projected by the model to the measured utility data. Comparison of two different types of measured data are covered by this guideline: monthly utility bills and hourly data.

6.3.3.4.1 Calibrate to Monthly Utility Bills and Spot Measurements. Clause 6.3.3.2.2 discusses the collection of monthly utility bills. Where available, not only should electric bills be used for comparison, but also any other heating fuels, such as natural gas or fuel oil, as well as spot measurements of key components and systems. This approach is not as reliable as comparing to hourly data since monthly utility bills present so many fewer data points to calibrate to. As such, comparing to monthly utility bills is only acceptable when hourly whole-building data are not available and cannot be collected.

Of the techniques described in this guideline, comparing energy use projected by simulation to monthly utility bills and spot measurements is relatively uncomplicated. After the model developed in Clause 6.3.3 is run using weather data that corresponds to the billing periods, the monthly simulated energy use, including electric energy, electric demand, and

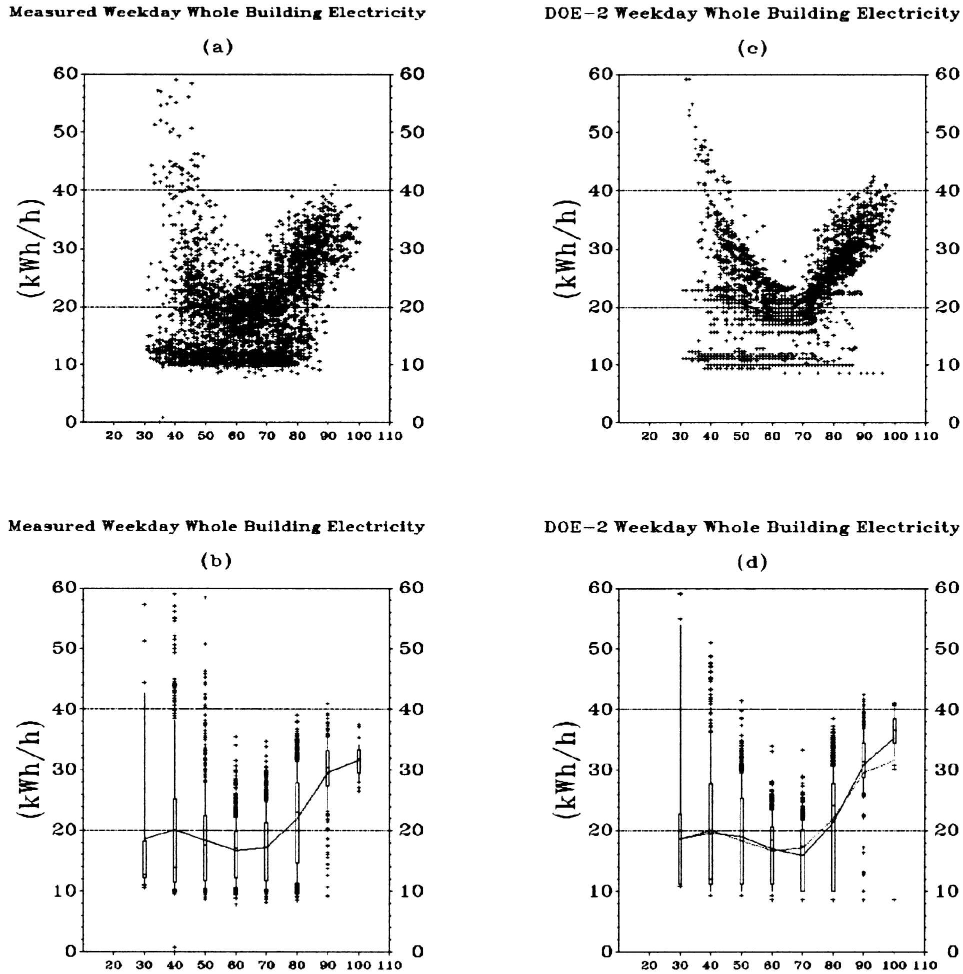

Figure 6.3-2 Example weekday temperature bin calibration plots. This figure shows the measured and simulated hourly weekday data as scatter plots against temperature in the upper plots and as binned box-whisker-mean plots in the lower plots.

energy use, including electric energy, electric demand, and any other fuels, is subtracted from the quantity listed in the utility bills, and the difference is divided by the bill amount. This calculation it is repeated for each month and then for the entire year. It is important that the simulated quantities be summed over the exact same days as the meter was read for the bills. Acceptable tolerances for this comparison shall range from ±10% for MBE to ±30% for CV(RSME) of the bill's represented energy use and/or demand quantity when using hourly data or 5% to 15% using monthly data (see 6.3.3.4.2.2).

6.3.3.4.2 Calibrate to Hourly Measured Data. When comparing simulation output to hourly measured data, two different techniques are used: graphical and statistical. There are a variety of graphical comparison formats, but in general, computer software is used to generate a graphic image from both the measured data and the simulation output data, and these two images are overlaid. Occasionally, a difference is found between these two datasets, which then forms the basis for a graphical image. Statistical methods use two different indices to determine whether the differences between the two datasets are within an acceptable tolerance.

It is recommended that both graphical and statistical techniques be used when comparing to hourly measured data. The statistical indices provide two numbers, which allow the modeler and any other interested parties to judge how closely the simulation output matches the measured data. The graphical techniques provide information regarding the time periods in which the two datasets diverge. By interpreting the graphics, modelers may infer what inputs may be responsible for such differences. In any event, users must report their statistical results and base their model tuning success on this technique.

6.3.3.4.2.1 Graphical Comparison Techniques. This guideline discusses four different graphical techniques including (1) weather day type 24-hour profile plots, (2) binned interquartile analysis using box whisker mean plots, (3) three-dimensional surfaces, and (4) three-dimensional color plots. The determination regarding which techniques to use for any given calibration is left to the judgment of the modeler. Additionally, the graphical presentation will often allow interested parties to review and comprehend these results.

1. *Weather day type 24-hour profile plots.* To produce hourly load profiles, measured power is divided into a few different day types, averaged by the hour, and then plotted against time. The day types should be selected to meet the project needs but may include up to eight day types: winter peak weekday, winter average weekday, winter average weekend day/holiday, summer peak weekday, summer average weekday, summer average weekend day/holiday, spring average weekday, and fall average weekday.

In Figure 6.3-2 only the weekday data are plotted in a fashion that includes a combination of vertical and horizontal juxtapositioning, temperature-based box-whisker-mean bins, and super-positioning of the mean bin line in the lower right graph. Similar analysis can be performed with weekend and holiday data (Bou-Saada 1994). In the upper left graph the hourly measured whole-building electricity use is plotted against hourly ambient temperature. In the upper right graph, the corresponding simulated electricity data for the same period are shown. Below each scatter plot are binned box-whisker-mean (BWM) plots. These plots show the whole-building electricity use as a function of outdoor temperature bins divided into 10°F segments. One final feature of these plots is that the measured data mean is superimposed as a dashed line onto the calibrated simulation data. The difference between mean lines in each bin provides a measure of how well the model is calibrated at a specific temperature bin. Likewise, the inter-quartile range (i.e., the distance between the 25th and 75th percentiles) represents the hourly variation in a given bin.

2. *Binned interquartile analysis using box whisker mean plots.* The superimposed and juxtaposed binned box-whisker-mean (BWM) plots display the maximum, minimum, mean, median, 10th, 25th, 75th, and 90th percentile points for each data bin for a given period of data. These plots eliminate data overlap and allow for a statistical characterization of the dense cloud of hourly points (scatter plots are still useful in showing individual point locations). The important feature to note about this plot is that the data are statistically binned by temperature. This feature allows for the bin-by-bin goodness-of-fit to be evaluated quantitatively and graphically. Using the box-whisker-mean plot combined with a scatter plot also allows one to visualize the data as a whole while simultaneously seeing the effects of the outliers in specific situations. Both of these features are important to the efficiency with which the graph conveys an accurate and consistent message to the viewer (Tukey 1977; Cleveland 1985).

Figure 6.3-3 is an example of a weekday 24-hour weather day type box-whisker-mean plot that shows the whole-building electricity use versus the hour-of-the-day for both the measured data and the simulated data in three weather day types.

The weather day types arbitrarily divide the measured data into groupings. For example, the summer peak weekday can be defined by selecting the five warmest non-holiday weekdays during June, July, and August using the actual weather data for the calibration period. The hourly load data for each of those identified days are then extracted from the utility data sets and the simulation output and compared. In a similar fashion, the summer average weekday data are prepared from the remaining weekday data (excluding the days used in determining the peak day data set) as are the other day types of interest.

Calibration criteria for this technique can be developed for energy use and demand profiles based on monthly, daily,

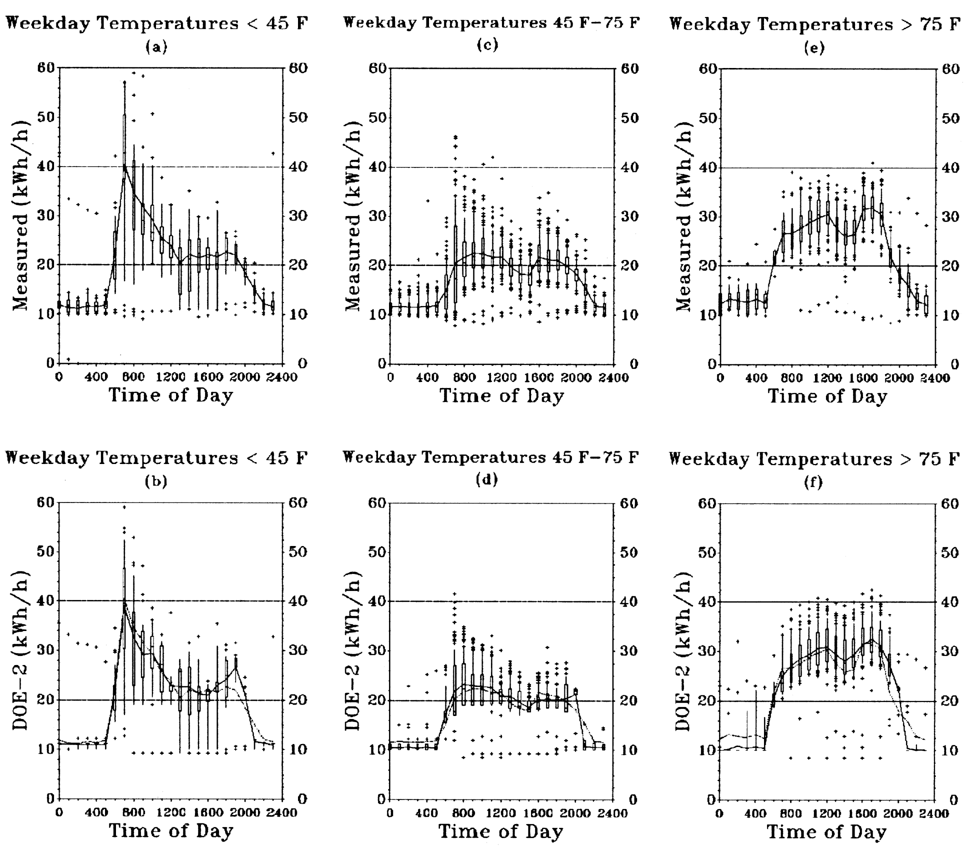

Figure 6.3-3 Example weekday 24-hour weather day type box-whisker-mean plots.

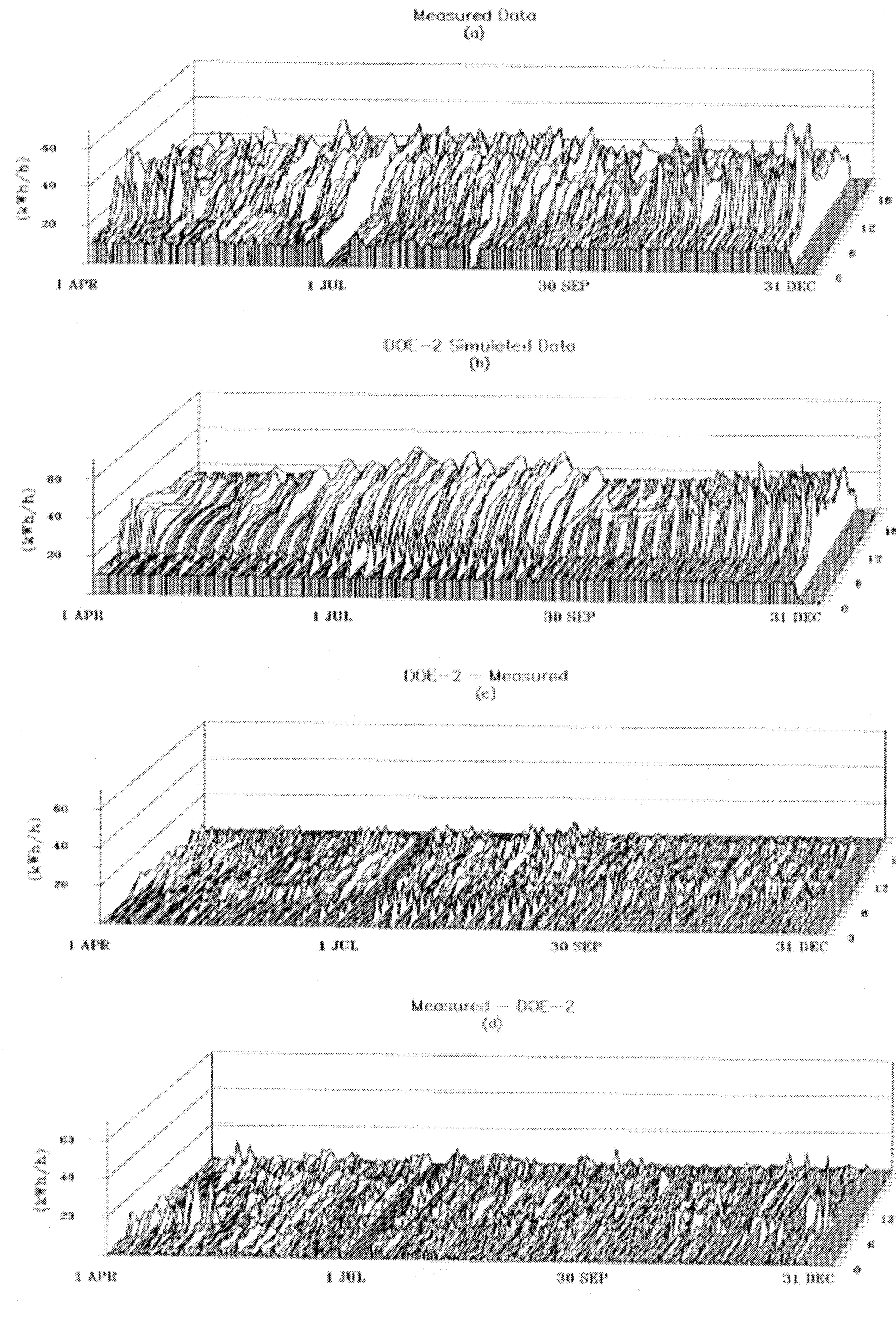

Figure 6.3-4a-d Example comparative three-dimensional plots: (a) measured data, (b) simulated data, (c) simulated-measured data, and (d) measured-simulated data.

and hourly agreement for each day type of interest. Acceptable calibration has been declared when models match to within ±2.5% monthly, ±10% daily, and ±20% for a minimum of 20 out of 24 hours for each day type.

3. *Three-dimensional surfaces.* In Figures 6.3-4a-d comparative three-dimensional surface plots show the monitored data in part (a), the simulated data in part (b), positive-only values of the measured data subtracted from the simulated data in part (c), and positive-only values of the simulated data subtracted from the measured data part (d).

Individual hourly differences may be visually detected over the entire simulation period using these plots, which allows the user to recognize patterns in the comparisons, such as the simulation program's overpredictions in the spring and fall mornings and afternoons and both over- and underpredictions in the late evening throughout the year. An obvious benefit of such plots is their ability to aid in the identification of oversights such as a daylight savings shift or misalignment of 24-hour holiday profiles (Bronson et al. 1992). One negative drawback associated with these graphs is the difficulty in viewing exact details such as the specific hour or specific day on which a misalignment occurs.

4. *Three-dimensional color plots.* Three-dimensional color plots serve a purpose similar to surface plots, but solve some of the latter's problems. Some model calibrators complain that surface plots obscure data that's behind "hills" or in "valleys." By substituting color for depth, some calibrators find they can more easily interpret the graphs. For further information, refer to the work of Craig Christensen as well as R.L. Wright.

6.3.3.4.2.2 Statistical Comparison Techniques. Although graphical methods are useful for determining where simulated data differ from metered data, and some quantification can be applied, more definitive quantitative methods are required to determine compliance. Two statistical indices are used for this purpose: hourly mean bias error (MBE) and coefficient of variation of the root mean squared error (CV(RMSE)) (Kreider and Haberl 1994a, 1994b; Haberl and Thamilseran 1996).

MBE is found by first calculating the difference between measured energy use and simulated energy use for a given hour. Such differences are then calculated for all the hours over a given time period, usually a month or year. The differences are summed and then divided by the sum of the measured energy use over the same time period. MBE is expressed as a percent error.

For example, if over the course of a year a building consumes 1,400,000 kWh, and the simulation model projects an annual energy use of 1,100,000 kWh, the MBE associated with this particular model is equal to: (1,400,000-1,100,000)/ 1,400,000 = 0.21, or 21%.

The MBE measures how close the energy use predicted by the model corresponds to the metered data on a monthly or annual basis. MBE, however, may be influenced by offsetting errors, so an additional index is necessary

The root mean squared error is typically referred to as a measure of variability, or how much spread exists in the data. For every hour, the error, or difference in paired data points, is calculated and squared. The sum of squares errors (SSE) are then added for each month and for the total periods and divided by their respective number of points, yielding the mean squared error (MSE), whether for each month or the total period. A square root of the result is then reported as the root mean squared error (RMSE).

The coefficient of variation of the root mean squared error, CV(RMSE) (%) (Draper and Smith 1981), is calculated by dividing the root mean squared error by the measured mean of the data. (**Note:** Show the equations for RMSE and CV(RMSE) here.)

CV(RMSE) allows one to determine how well a model fits the data; the lower the CV(RMSE), the better the calibration (the model in this case is the simulated data). Therefore, a CV(RMSE) is calculated for hourly data and presented on both a monthly summary and total data period.

It's much easier to achieve a lower MBE than a CV(RMSE). MBEs are frequently reported in a range ±5% to ±10%, but the very best empirical models of building energy use performance (e.g., artificial neural networks used with a large commercial building) were only capable of producing CV(RMSE) in the 10% to 20% range. Typically, models are declared to be calibrated if they produce MBEs within ±10% and CV(RMSE)s within ±30% when using hourly data or 5% to 15% with monthly data. See clause 5.3.2.4 for further information on this topic.

6.3.3.5 Refine Model Until an Acceptable Calibration is Achieved. If the statistical indices calculated during the previous step indicate that the model is not sufficiently calibrated, revise the model and compare again to measured data. Numerous iterations of this process may be needed to obtain acceptable calibration levels.

6.3.3.6 Produce Baseline and Post-Retrofit Models. This clause describes the development of both of these models, as well as how to proceed if it is not possible to calibrate simulation models to both the baseline and post-retrofit buildings.

6.3.3.6.1 Baseline Model. The baseline model represents the building, as it would have been in the absence of the retrofit project. Typically, the baseline represents the state the building was in before the retrofit commenced. Occasionally, a building owner would have made some change to the building in the absence of the retrofit project. For example, consider the case when an owner plans to replace a chiller and engages with a contractor to provide a high efficiency chiller. The building owner and the contractor may agree that the appropriate project baseline is the average efficiency chiller the owner would have purchased and installed had there been no contract with the energy performance contractor. In such cases, calibrate the simulation model to the building as it existed before the retrofit, and then modify the model in accordance with any agreed on baseline conditions.

6.3.3.6.2 Post-Retrofit Model. The post-retrofit model represents the building as it is when the retrofit project is complete. Ideally, the post-retrofit model would represent the building after start-up and commissioning procedures are completed. The post-retrofit model, however, may represent whatever state the building is in when the owner and the contractor agree the project is substantially completed and the time period for measuring savings begins.

Often it is desirable to calibrate the post-retrofit model to ensure that the newly installed measures are accurately represented. This step can serve to both check for proper measure operation as well as correct modeling techniques. When producing a post-retrofit calibrated model after a baseline model has already been calibrated to the building, minimize the amount of duplicated work by limiting data collection activities to investigating changes between the baseline and post-retrofit building. For example, confirm the installation and characteristics of installed measures, and verify measure operation. Confirm as well whether changes to building operation (baseline shifts) have occurred since the calibration of the baseline model. Modify the calibrated baseline model to develop the post-retrofit model, and calibrate that model to post-retrofit data. Keep in mind that only two types of model changes are valid: (1) baseline changes applied equally to both the baseline and post-retrofit models and (2) measure-related retrofit changes that are applied only to the post-retrofit model.

6.3.3.6.3 What to Do When It Is Not Possible to Calibrate Simulation Models to Both the Baseline and Post-Retrofit Buildings. Ideally, both baseline and post-retrofit models are calibrated to measured utility and weather data. In the event that insufficient information is available to calibrate both of these models, then either model may be calibrated to measured data, and the other developed by modifying the calibrated model.

In general, there are four reasons why it may not be possible to calibrate both baseline and post-retrofit models to measured data: (1) the collection of hourly utility data did not commence until the measures were installed, (2) savings must be verified before sufficient time has elapsed to collect a minimum amount of post-retrofit data, (3) the measures are installed in a new building, and (4) the building configuration or operation has changed since the installation of the measures. Following is a description of each of these scenarios and instructions associated each one.

1. *The collection of hourly utility data did not commence until the measures were installed.* Conduct a site visit before the measures are installed in accordance with the procedures described in Clause 6.3.3.2.4 above. When the measures are installed, also install equipment to collect hourly utility data, perform spot measurements to verify operating characteristics, and continue to collect data for a year. During that time period, conduct an additional site survey to verify the installation of the measures. Finally, calibrate the post-retrofit model to the measured data and modify that model to represent the baseline model.

2. *Savings must be verified before sufficient time has elapsed to collect a minimum amount of post-retrofit data.* Although the most accurate results may be obtained by collecting a year's worth of pre-retrofit and post-retrofit data, it is possible to verify savings before that much time has elapsed, provided the baseline model was calibrated to hourly data. When such is the case, visit the site after the retrofit is complete and verify that the measures are installed and are functional. Clause 6.3.3.3 above provides guidance for verifying measure characteristics. To produce the post-retrofit model, modify the calibrated baseline model so that it reflects the characteristics and functions of the installed measures.

3. *The measures are installed in a new building.* When energy conservation measures are incorporated into a new construction project, the baseline building will not be a building that has ever existed. When this is the case, calibrate a simulation model to the post-retrofit building and then modify that model to represent the baseline building. The process of arriving at the characteristics of the baseline building may require detailed certification of every input using values obtained from "average" sources, code books, or through negotiation.

4. *Building configuration or operation has changed since the installation of the measures.* When building configuration or operation changes after a baseline has been agreed upon by the buyer and seller (baseline shift), calibrated simulation may be applied to simulate the savings that would have been achieved had those changes never occurred. First, calibrate the simulation model to the building as it exists during the calibration period. Then modify the calibrated model to produce baseline and post-retrofit models that are consistent with the agreed upon baseline. When doing so, inasmuch as it is possible, modify the calibrated model so that the changes in building configuration or operation are restored to the conditions contained in the agreed upon baseline. For example, if hours of operation change, modify the calibrated model so that hours of operation are those in the agreed upon baseline.

6.3.3.7 Calculate Savings. Savings are equivalent to the energy use of the baseline model minus the energy use of the retrofit model. To simulate savings, first ensure that all inputs to the baseline model and the post-retrofit model are consistent. Next select the appropriate weather data set and run both models. Then, compare the energy use projected by both models. Lastly, when there are multiple measures that interact and total savings need to be disaggregated by measure, a sequential modeling process is required to account for the interactive effects.

6.3.3.7.1 Ensure That All Inputs to the Baseline Model and the Post-Retrofit Model Are Consistent. When calculating savings, the only difference between the inputs to the baseline model and the post-retrofit model are those directly related to the measures. Investigate any inconsistencies between the two models and correct them. For example, if building operation changes between the production of the baseline model and the post-retrofit model, modify the post-retrofit model schedule so that it is consistent with the baseline model.

6.3.3.7.2 Select the Appropriate Weather Data Set and Run Both Models. Two different options are available for selecting weather data sets. If it is desired to simulate savings for a specific year, use weather data from that year. If it is desired to simulate savings for a typical year, use typical weather data. Once a weather data set is selected, run both the baseline model and the post-retrofit model using the same weather data.

6.3.3.7.3 Calculate Savings. To calculate savings, subtract energy use and or demand projected by the post-retrofit model from energy use/demand projected by the baseline model.

6.3.3.7.4 Accounting for Individual Savings of Multiple Interacting Measures. When multiple measures are combined in a single building, they often interact. The savings achieved by the combined interacting measures are different from the sum of savings achieved had each measure been implemented individually (Wolpert et al. 1992). For example, consider the case when a high efficiency motor retrofit is combined with a variable speed drive. The savings realized by the motor retrofit will be lower if it is controlled by the variable speed drive. The variable speed drive savings vary depending on whether it is controlling the old inefficient motor or the new high efficiency motor.

To allocate interactive effects among measures, first rank measures in order. This order may be based on cost-effectiveness, the sequence in which measures would likely have been implemented had they been implemented individually, or any other basis agreed upon by buyer and seller.

Next the measures are sequentially simulated as follows: The baseline model is modified so that it includes the highest ranked measure. The savings associated with this measure are then estimated by comparing the baseline model to the modified baseline model that includes the measure in question. This first modified model is then modified again so that it now includes both the first and the second measure. The savings associated with second measure are then estimated by comparing the model with the first measure to the model with both the first and second-ranked measures. Continue adding measures to the mix and estimating savings by comparing the model with the most recent added measure to the previous model with one fewer added measure. This process continues until a model is developed that includes all the measures. This final model should be identical to the post-retrofit model.

6.3.3.8 Report Observations and Savings. When the savings analysis is complete, prepare a report on the estimated savings. It is recommended that such a report include:

1. *Executive Summary:* Provides an overview of the project and the estimated savings.
2. *Baseline Building:* Describes the building before any measures were installed, including size, occupancy, and relevant mechanical, electrical, and other building systems.
3. *Measure Descriptions:* For each measure, provide a description and explain why it reduces energy use/demand.
4. *Simulation Plan:* Include a copy of the simulation plan that was used to guide the process.
5. *Methodology:* Describe the process by which savings were estimated. Follow the format provided in this guideline.
6. *Observations:* For each methodology step, describe the information either collected or produced, including a summary of collected data, model inputs, calibration indices including graphical and statistical data, and any other remarkable observations.
7. *Results:* For each measure and savings estimate, show the baseline value, the post-retrofit value, and the difference.
8. *Appendices:* Provide information too detailed for the main body of the report. Ensure that sufficient model development and calibration documentation is provided to allow for accurate re-creation of the baseline and post-retrofit models by informed parties, including:

   - on site survey documentation,
   - spot and short-term measurement documentation,
   - calculations made to process observations into simulation inputs,
   - utility data used for calibration,
   - weather files if non-standard data/modifications are used,
   - simulation inputs and outputs,
   - show which inputs were used to simulate the baseline building,
   - show which inputs were changed from the baseline for each measure,
   - include summary results and cross-check worksheets.

Submit electronic copies of all simulation-input files with the report to allow for verification and to provide a permanent archive of the savings estimate.

6.3.4 Modeling and Uncertainty Analysis. Uncertainty analysis shall be based upon the procedures described in Clause 5.2.11, "Savings Uncertainty Analysis." The analysis will utilize values as determined in Clause 6.3.

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7. INSTRUMENTATION AND DATA MANAGEMENT

7.1 Introduction

This clause discusses the selection and application of instrumentation used in measuring the information required to evaluate energy and demand savings. It includes a discussion of data acquisition and sensor types, application methods (survey, temporary and permanent installation), calibration complexity, uncertainty analysis, data validation methods, and measurement system maintenance. Instrumentation selection is dependent upon clear definition of project requirements, cost constraints, and completing a thorough sensitivity analysis of the proposed method of measurement utilizing expected data.

7.2 Measurement Procedure

An appropriate measurement procedure should be developed prior to installation of any measuring instrument to enhance and ensure the credibility of the information it is to gather (Lyberg 1987). The procedure should include the following:

- Measurement point name.
- Measurement type.
- A description of the measuring instrument.
- Installation method.
- Installation location with a description of suitable operating conditions.
- Expected range of values with the expected uncertainty.
- Method and rigor of calibration required.
- Method and rigor of measurement system verification and data validation required.
- Information to be logged, such as specifications, installation date, and calibration records and maintenance records. It is vital to maintain a historical record of each measurement point.
- Minimum level of data performance (e.g., how much missing or erroneous data will be tolerated before recalibration or replacement is required to occur).
- Period of recalibration.
- Alternate methods of obtaining the required information if the instrument is down for repair or recalibration or if data are missing or invalid for any reason.

- Allowable methods of error remediation.
- Applicable maintenance requirements.

7.3 Instrumentation

The quality of any measurement is dependent upon the effect of the measurement location, the capability of the measurement sensor and the data-recording instrument, and the sampling method employed. If available, one may consider making use of pre-existing equipment. To be even considered, they must first meet the data integrity requirements of their new application, but the added costs for calibration and maintenance may make their use prohibitive.

Data Recording Devise. Selection of a data recording devise is dependent upon the quality (accuracy, precision, drift, rate of response), quantity and type of inputs required, installation restrictions, signal conditioning, measurement range, and the resources available to purchase and support it. Digital data acquisition instrumentation is now the typical hardware of choice to gather field data. This is true whether the data are gathered by a portable instrument or by a permanently installed building automation system (BMS). However, BMS hardware is typically not designed for this particular application and its ability must be demonstrated before it can be used with confidence (Heinemeier et al. 1996). It is also noted that BMS control requirements are not always compatible with measurement and monitoring requirements. Characteristics to consider include the following:

Scan Rate. It is always best to strive for an order of magnitude higher scan rate than the period of the process being measured. This is especially true with dynamic processes.

Time Measurement Characteristics. Performance measurements are directly affected by the resolution, accuracy, and precision of the DAS internal clock per unit of time. Most systems provide reasonable capabilities.

Engineering Unit Conversion Methods. Converting of sensor output to engineering units is typically provided by most equipment utilizing the linear scalar and offset method ($y = mx + b$). Advanced systems provide for polynomial curve fitting or point-to-point interpolation. Many systems offer some form of temperature look-up tables or standard equations for RTDs and/or TCs. Engineering units are extremely helpful in performing on-line sensor calibrations, trouble shooting, and interchannel calculations (using concurrent data from more than one channel).

Math Functions. It is desirable to have the ability to manipulate the sampled data as it is scanned. One may also need to determine individual channel interval averages, minimums, maximums, standard deviations, and samples per intervals and perform interchannel calculations including averages and loads. Building automation systems typically are not provided with the ability to perform time interval-based averaging intervals; however, some newer systems can be configured to provide the required data.

Data Archival and Retrieval Format. Most limited channel data loggers provide for archiving of averaged or instantaneous measured data in time series record format that can be directly loaded into a spreadsheet. Using a building automation system as the data-recording instrument should only be done after careful review of its capabilities. Some building automation systems cannot record and archive data on a regular interval; however, some newer systems can be configured to provide the required data.

Communications. Most data loggers have RS232 communication capability, but it may also be desirable to have a modem, to enable retrieval of data from off-site.

See clause 4 for definitions of digital data acquisition system specification characteristics.

Sensors. Sensor selection is dependent upon the quality (accuracy, precision, drift, rate of response), quantity, installation restrictions, method of measurement required, signal output requirements (or signal conditioning), measurement range, turndown, and the capabilities of the intended data recording devise and the resources available to purchase and/or support it. Typical measurements include runtime, electric demand and energy use, temperature, fluid and air flow, thermal energy, psychrometric properties such as relative humidity and wet-bulb temperature, pressure, and ambient weather conditions such as wind speed, wind direction, and horizontal insolation. See Annex A1 and A5 for a detailed discussion of sensor characteristics.

7.4 Measurement Techniques

Measurement technique will vary depending upon the requirements of the specific measurement application. Such requirements include measurement budget, limits of uncertainty in the measured result, and the time required to gather the necessary data.

7.4.1 Duration Classification. It is helpful to classify the time required to gather the necessary data into three categories: spot measurements, short-term measurements, and long-term measurements.

7.4.1.1 Spot Measurements. Spot measurements typically are made with portable survey or hand-held instruments over a brief period such as <1 hour per point or test condition. Instrumentation is not left in place and the data gathered are only a small sample of actual conditions. This method is typically employed to determine existing conditions or to verify other measured data. Example instruments include clamp-on power meters, hand-held surface temperature indicators, and portable ultrasonic flow or energy meters.

7.4.1.2 Short-Term Measurements. Short-term measurements are typically made with temporarily installed instruments over a short-term test period (one day to six months). Both for safety and data access expense, the test period typically would not exceed six months. It should be noted that temporary installations could impact normal system operations. The availability of one- to four-channel battery-powered programmable data acquisition systems with sufficient memory and accuracy has made this the method of choice for many applications.

7.4.1.3 Long-Term Measurements. Long term measurements (six months or longer) typically utilize permanently installed instrumentation. This is primarily due to safety limitations and the need for data reliability. The wiring between sensor and logger may or may not be required to be placed in conduit. It is typically applied to the more complex measurement applications, which require many different measurement types, process calculations, and extended evaluation periods. Remote data access is often employed.

7.4.2 Methods. Every investigator of energy and demand savings desires to employ the least complex measurement method with sufficient accuracy and minimum expense to achieve the required uncertainty in the result. Static or steady-state systems, those that provide a narrow range of conditions or vary little with time, are the simplest to evaluate and may only require the most basic of measurement methodologies. Dynamic or non-steady-state systems, those that provide a wide range of conditions or vary significantly with time, are more complicated to evaluate. This is especially true with systems that provide a wide range of rapid and unpredictable changes in conditions. These systems typically require many different measurement types, process calculations, and an extended evaluation period.

Redundant sensors and on-line checks should be used to reduce the impact of equipment failures. This is especially true with the parameters that directly relate to the calculation of energy flows. See Annex A3 and Annex A4 for detailed discussion of measurement approaches for various measurement types.

7.5 Calibration of Instrumentation

7.5.1 Recommendations. It is highly recommended that instrumentation used in measuring the information required to evaluate energy and demand savings be calibrated with procedures developed by the National Institute of Standards and Technology (NIST). Primary standards and no less than third order NIST-traceable calibration equipment should be utilized wherever possible.

7.5.2 Calibration Requirement Classifications. The level of calibration required will be dependent upon the rigor of the test plan. Listed below are suggested requirements for minimum, optimal, and advanced or very rigorous test plans. It is highly recommended that any equipment that is used for calibration and verification be appropriately calibrated.

7.5.2.1 Minimum Requirements (a). Instrumentation accuracy specification is accepted. A simple through-system (end-to-end) calibration is performed in the field at a known condition (such as the process or ambient condition). If necessary, the instrument is adjusted or an appropriate offset is determined and correction is made at the data acquisition system (DAS) or in the data. Changes made are verified.

7.5.2.2 Optimal Requirements (b). Instrumentation is provided with a qualitative multi-point factory calibration (including minimum, typical, and maximum). Multiple-point through-system (end-to-end) calibration is conducted in the field. If necessary, the instrument is adjusted or an appropriate offset is determined and correction is made in the DAS. Changes made are verified.

7.5.2.3 Advanced/Rigorous Requirements (c). Instrumentation is calibrated at an in-house or independent facility at minimum, typical, and maximum conditions prior to its placement in the field. Multiple-point through-system (end-to-end) calibration is conducted in the field. Appropriate correction factors are determined. The instrument is adjusted or corrections are made in DAS. Changes made are verified.

7.5.3 Recalibration of Instrumentation. The period of recalibration should be provided in the measurement procedure. If data validity is in doubt, recalibrate. Recalibration should focus on the most critical measurement points.

7.6 Measurement System Verification and Data Validation

7.6.1 Measurement System Verification. In this case, verification determines the installed functionality and uncertainty of the measurement system. The method and rigor should be defined in the test's measurement procedure. The most stringent method to verify the uncertainty of a measurement system result is an in-situ, through-system calibration of each measurement system input with other instruments of known uncertainty or by the use of a different measurement method of known uncertainty. The most basic method compares individual measurements with other similar measurements; comparison sources may be from the measurement system or field-installed gauges, portable survey, or handheld instruments. Clause 7.6.3 identifies computerized data validation methods that can also be used to verify that the measurement system is in good working order. The conservation of energy and flows is the most comprehensive.

If the measurement system employs the ability to archive time series data and recover it remotely, the data retrieval process should be evaluated.

7.6.2 In-Situ Data Validation Methods. Internal data acquisition system sensors, such as resistance or temperature, or external inputs, such as resistance, of known value should be archived as a check channel along with measured data to provide an indication of A/D quality and drift. Subsequent computerized data validation should flag conditions that are out of range.

7.6.3 Computerized Data Validation Methods (Mazzucchi et al. 1996). Archived data that does not pass the following validation checks would be flagged for further investigation.

Time-step. The time interval between consecutive time series records is compared with the programmed interval.

Rational check. Each archived data entry is determined to be numerically correct, e.g., does not contain more than one decimal point or contain unnecessary characters.

Range gate validation. Each measurement is compared against an expected minimum and maximum value.

Relational checks. Calculation results, such as thermal load or coefficient of performance using individual time series records or daily totals, are compared with expected values. If multiple measurement methods are available, their results can be compared.

Graphical validation. Selected measured data or calculated results can be plotted to indicate their change with time or how they compare with one another.

Statistical checks (mean, standard deviation, and goodness of fit). Both from the beginning of the experiment and over the reporting interval, the minimum, maximum, mean, and standard deviation of measured data and calculation results are calculated. Values are scanned to detect large deviations or if trends exist.

Process heat balance/conservation of flow or energy methods. If all components of the process heat balance are measured, does the heat balance yield unity; e.g., does the sum of the energy used and the energy delivered divided by the energy rejected yield one. Consistent results outside 0.9 to 1.1 should be investigated for measurement or analysis error.

7.7 The Uncertainty of the Measurement

It should be understood that any statement of measured savings includes a degree of uncertainty whether or not it is provided. The uncertainty in savings can be attributed to errors of assumptions, measurement errors (both in the independent and dependent variables), sampling errors, and to errors in the regression model, which include predictive and normalization errors. Though measurement errors are relatively well known and the complex methodology of estimating their effect is adequately covered in classical engineering textbooks (Dieck [1992] for example), measurement errors are not well understood by the practitioner who may simply ascribe to manufacturers published data (which are typically not provided in a suitable or consistent context). A proper uncertainty analysis evaluating the instrumentation under consideration and data expected to be gathered should be performed prior to testing to refine the measurement system to the level of uncertainty desired. After the test, the uncertainty analysis should be reevaluated utilizing the actual data gathered during the test. See Annex B for detailed discussion of uncertainty.

Measurements made in the field are especially subject to potential errors. In contrast to measurements made under the controlled conditions of a laboratory setting, field measurements are typically made under less predictable circumstances and with less accurate and less expensive instrumentation. Field measurements are vulnerable to errors arising from variable measurement conditions (the method employed may not be the best choice for all conditions), from limited instrument field calibration (typically more complex and expensive), from simplified data sampling and archiving methods employed, and from limitations in the ability to adjust instruments in the field.

With appropriate care, the conscientious measurement practitioner can minimize many of these sources of error. But what differentiates this practitioner's result from that of someone who does not consider sources of error or does little to minimize sources of error? The conscientious measurement practitioner has developed a procedure by which an uncertainty statement can be ascribed to the result and has also optimized the measurement system to provide maximum benefit for the least cost. The practitioner who does not consider sources of error probably has not maximized benefits.

7.8 Measurement System Maintenance

7.8.1 Instrumentation Maintenance.

7.8.1.1 When to Check. The interval for checking measurement results will depend upon the criticality of the measurement point to the overall result and the cost-effectiveness of doing or not doing so. The timeliness of correcting any problem should always be taken into account. If data are checked on a weekly basis, it may take an additional two weeks to correct a discovered problem.

7.8.1.2 When to Recalibrate. For critical measurement points, which are a part of a long-term testing project, a six-month to yearly calibration interval is highly recommended. Long-term tests should also be subject to a post-test calibration. All spot measurement or temporary instrumentation should have had an appropriate calibration within the past six months.

7.8.1.3 When to Replace. The decision to replace an ailing sensor is dependent upon the degree of error introduced in the measured result and the cost of replacement (purchase, calibration, and installation). For noncritical measurements, where sufficient data have previously been gathered, the time of sensor failure may only need to be noted and the experiment can proceed without interruption. For critical measurements, whose continued error could lead to a failed experiment, it is probably better to recalibrate once, then replace as soon as possible if the sensor continues to show signs of nonperformance. It is always important to verify the sensor's nonperformance with other data sources; the "wayward" sensor may, in fact, be fairly representing actual conditions.

Being forced to replace a sensor mid-test often adds to the overall uncertainty of the results when compared to the uncertainty of the result had the original sensor not failed. A complete recalibration of the measurement system may be required. This is especially true with matched sensors used to determine differential temperature. But the alternative is no data at all, which may lead to a failed experiment.

7.8.1.4 When Has the Experiment Failed? The experiment fails when the path from the baseline condition to the measured savings result is indeterminate. This can occur when new data reveal that the agreed upon baseline did not fairly represent actual conditions. It can occur when the system being tested is altered mid-test so radically that it no longer represents the system being tested. It can also occur when measurement system failures prevent the determination of a result within the acceptable range of uncertainty. It is important that test participants make contingent plans up front for these occurrences.

7.8.2 Dealing with Data Collection Errors and Lost Data.

7.8.2.1 Data Collection Errors. No collected data are without error. Data collection methodologies differ in degree of rigor and, therefore, in the number and source of errors and the resultant degree of uncertainty. A minimum level of data performance should be established as part of the measurement procedure. This level should define the overall results calculation uncertainty needed to provide the appropriate confidence level to the user. Higher levels of data accuracy may have a dramatic affect on the cost of verification and data validation and should be decided as part of the overall project economics.

Errors in the data are identified through calibration and data validation methods as described in 7.4 and 7.5 above. Errors that have been identified will require some form of remediation. The data may be omitted, adjusted by recalibration, adjusted by interpolation between preceding and acceding data, adjusted to a nominal value, or ignored. The allowable methods of error remediation should also be identified in the measurement procedure.

7.8.2.2 Non-Recoverable Data. Data can be lost for many reasons, including:

- Sensor failure (power failure, broken sensor)
- Data acquisition system failure (loss of interface with the sensor, power interruption, program or data storage scram)
- Data archive failure (data transfer error or loss)

Data loss must be detected and corrected as soon as possible. Even with the best of preventive measures, 100% data capture is nearly never achieved. It is important, therefore, that a methodology be developed and provided in the measurement procedure, stating how data that is missing or determined to be incorrect will be accounted for and its uncertainty documented in the final analysis.

Generally, missing data can be handled by omitting analysis for the interval of lost data or substituting a rational replacement value, which may be fixed, interpolated, synthesized, or calculated from known information (Haberl et al. 1990). Large gaps in the whole data set are more difficult to restore. Irrespective of the method chosen, always maintain a record of the raw data and instructions on how the replacement value was obtained in the instrument log.

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(This informative annex is not part of ASHRAE Guideline 14 but is provided for informational purposes only.)

ANNEX A: PHYSICAL MEASUREMENTS

A1 Sensors

In-situ field testing will require measurements of various physical characteristics of the equipment in question. Sensor selection is dependent upon the quality (accuracy, precision, drift, rate of response, range, output), quantity, installation restrictions, and method of measurement required and the resources available to purchase and support it. This clause provides a review of techniques applicable to measurement of runtime, electric demand and energy use, temperature, liquid, air and steam flow, thermal energy, psychometric properties (humidity), pressure, and outside weather conditions. A list of potential measurement instrumentation is given in Table A1-1.

A1.1 Power Measurement Equipment. Real power, power that has the ability to perform work, can be measured directly using watt transducers, devices that determine power from voltage and current sensors, making the necessary internal calculations to account for power factor and eliminate any bias in the measurement. Watt-hour transducers, devices that integrate power over time, are available to give the engineer real energy use data and eliminate the error inherent in assuming or ignoring power factor. Stand-alone watt-hour transducers are available to produce pulses representative of some number of watt-hours. These pulses are typically input to a pulse-counting data logger for storage and later retrieval and analysis.

An alternative technology involves combining the metering and data logging functions into a single piece of hardware. This “integrated” metering approach incorporates “virtual” digital watt-hour meters into a single solid-state device capable of monitoring a number of single-phase power channels. Whereas pulse-counting technology makes kW and kWh information available to the user, the integrated approach allows access to much more information. In addition to kW and kWh, each defined power channel can record voltage, current, apparent power in kVA, kVAh, and power factor. Many integrated meter/monitors have the ability to perform wave-form analysis, capturing harmonic information for both voltage and current wave-forms. They may be time sampled or continuous reading.

Until recently, most loads were “linear”; that is, the nature of the load remained essentially constant regardless of the applied voltage. These linear loads resulted in smooth sinusoidal voltage and current wave-forms. Conventional meters usually measure the average value of the amplitude of the waveform. Some meters are calibrated to read the equivalent root-mean-square (rms) value, equal to 0.707 times the sinusoidal peak value. This type of calibration is a true representation only when the waveform is a nondistorted sine wave.

TABLE A1-1
List of Potential HVAC Sensors

<u>Temperature</u> Thermometer Thermocouple RTD Thermistor I. C. temperature sensor	<u>Psychrometric Properties</u> Dew/frost Psychrometer Thin film polymer Mechanical (dimensional) Dielectric crystal Chilled mirror	<u>Air Flow</u> Pitot tube Hot-wire anemometer Rotary device Flow nozzles
<u>Liquid Flow</u> Orifice Venturi Flow nozzle Turbine Vortex Magnetic Ultrasonic Paddlewheel Impact Mass-coriolis Mass-thermal Transducers, kJ or Btu	<u>Air Pressure</u> Manometer Pressure gage Pressure transducer Pressure transmitter	<u>Hydraulic Pressure</u> Manometer Pressure gage Pressure transducer Pressure transmitter Rotational speed Contact tachometer Noncontact tachometer Strobes Reflective tachometer
<u>Electrical Power</u> Watt-hour meters Watt transducers	<u>Electrical Current</u> Clamp-on amp meter Current transformer	<u>Electrical Voltage</u> Voltmeter Multimeter Potential transformer

With the advent of computers, uninterruptable power supplies, and variable speed motor drives, nonlinear waveforms are more the norm. When distortion occurs, the relationship between average readings and true rms values changes drastically. Peak-sensing and averaging meters are inaccurate and inappropriate technologies for the measurement of distorted waveforms. Digital sampling technology is the recommended method of measuring nonsinusoidal waveforms. Solid-state digital metering equipment simultaneously samples voltage and current to produce instantaneous values that are stored in memory along with their product and individual squares. Periodically, the meter calculates root-mean-square and average values to provide true rms power and energy use data. True rms power and energy metering technology, based on digital sampling principles, is recommended over individual voltage and current readings due to its ability to accurately measure distorted wave forms and properly record load shapes.

Electrical energy use measurements taken with true rms wattmeters are preferred over volt × amp measurements because of their ability to capture power factor measurements for electrical equipment that may have reactive loads (e.g., fluorescent lighting, motors). However, volt × amp measurements can be used in purely resistive electrical loads (e.g., incandescent lighting, electric heaters without motor-driven blowers).

A1.2 Runtime. Measurement and verification of energy savings often involve little more than an accurate accounting of the amount of time that a piece of equipment is operated or "on". Constant load motors and lights are typical of this category of equipment that need not be metered with full-featured rms power metering equipment to establish energy use. Self-contained battery-powered monitoring devices are available to record equipment runtime (and in some cases, time-of-use information). This equipment provides a reasonably priced, simple to install, solution to energy savings calculations. Runtime measurements are typically applied to dedicated single-circuit devices.

A1.3 Temperature. The computerized measurement of temperature has become an off-the-shelf technology. Most commonly used computerized temperature measurements use one of four basic methods for measuring temperatures: resistance temperature detectors (RTDs), thermoelectric sensors (thermocouples), semiconductor-type resistance thermometers (thermistors), and junction semiconductor devices, which are also called integrated circuit temperature (IC) sensors. Required accuracies and available budget will drive the selection of data logging device and the type of sensor to be used. Measurement accuracy is dependent upon the type of sensor, the sensor method of measurement (direct insertion, thermowell, or surface temperature), the absolute temperature, the vibration level of the measurement location, the distance and routing between the sensor and the data logging device, and the data logging device's method of reading the sensor input.

A1.3.1 Resistance Temperature Detectors (RTDs). The most common method of measuring temperature in the energy management field is with RTDs. RTDs are metallic devices whose resistance changes with temperature. They are among the most accurate, reproducible, stable, and sensitive thermal elements available. These devices are economical and readily available in configuration packages to measure indoor and outdoor air temperatures as well as fluid temperatures in chilled water or heating systems. Considering their overall performance, the most popular RTDs are 100 and 1000 ohm platinum devices in various packaging including ceramic chips, flexible strips, and thermowell installations in either 2-, 3-, or 4-wire configurations, with or without current transmitters. Applications utilizing 4-wire RTDs, which all but eliminate lead length and path issues, and a data logging device with a pulsed constant current source (to reduce self-heating effects) can measure temperatures to within 0.01°F if properly calibrated. Three-wire RTDs moderately reduce the effect of the long leads in an appropriately designed bridge circuit (0.25°F). Two-wire RTDs must be field calibrated to compensate for lead length and should not have lead wires exposed to conditions that vary significantly from those that are being measured (0.5°F). Factory matched and calibrated sensors with current transmitters can be utilized with data logging devices that do not have 4-wire RTD measurement capability to improve accuracy (0.1°F). These also reduce lead wire effects. Most data logging equipment allows for direct connection of RTDs by providing internal signal conditioning and the ability to establish offsets and calibration coefficients. Some types of RTDs tend to be more prone to failure at high temperatures or under high vibration. If it's a long-term installation, the right RTD (or a thermocouple) should be chosen for these harsh conditions.

A1.3.2 Thermocouples (T/Cs). In thermocouple thermometry, the magnitude of the voltage is dependent on the type of material and the temperature difference. The most commonly used thermocouple materials are platinum-rhodium (Type S or R), chromel-alumel (Type K), copper-constantan (Type T), and iron-constantan (Type J). Though thermocouples are economical and reasonably accurate, though less accurate than RTDs, they require cold junction compensation and their output signal is weak, making them sensitive to electrical noise and requiring the use of amplifiers and wide spans. They are also vulnerable to stress and vibration. Once a thermocouple has been placed in service, it is, in effect, never the same. Thermocouples are used in the laboratory for fast response averaging or differential temperature thermal arrays or in the field when accurate temperatures are required at high temperatures and high vibrations. T/Cs are usually cheaper than RTDs.

A1.3.3 Thermistors. Thermistors are semiconductor devices whose resistance changes with temperature. They offer high sensitivity and fast linear response. At high resistance, they can be very accurate over narrow ranges. One of the primary differences between thermistors and RTDs is that thermistors have a very large negative resistance change with temperature. Thermistors are not interchangeable, and their temperature-resistance relationship is very nonlinear. They are fragile devices and require the use of shielded power lines, filters, or DC voltage.

A1.3.4 Integrated Circuit Temperature Sensors. Certain semiconductor diodes and transistors also exhibit reproducible temperature sensitivities. Such devices are usually ready-made integrated circuit (IC) sensors and can come in various shapes and sizes. These devices are occasionally found in HVAC applications where their low cost and strong linear output over a narrow range are requirements. They are typically found in averaging or multi-point temperature sensors and in some Btu meters. IC temperature sensors have a moderately good absolute error, but they require an external power source, are fragile, and are subject to self-heating errors.

A1.4 Psychrometric Properties. Obtaining accurate, affordable, and reliable humidity measurement has always been a difficult and time-consuming task. Recently, such measurements have become more important in HVAC applications for purposes of control, comfort, system diagnosis, and performance evaluation. The amount of moisture in the air can be described by several interchangeable parameters including relative humidity, humidity ratio, dew-point temperature, and wet-bulb temperature.

The instruments that use the dew-point method directly measure the amount of moisture in the air. Instruments that use the relative humidity method do not actually "measure" the humidity but rather measure the effect of moisture using an indirect measurement. Relative humidity measurements include the evaporation psychrometer, electrical resistance or conductivity, elongation, capacitance-reactance, infrared, radio-frequency, and acoustic measurements. Instrumentation used to measure relative humidity or dew point are available from several vendors and installation is relatively straightforward. Calibration can be a little tricky. See A2.2.2 for a discussion of sensor calibration.

A1.5 Liquid Flow. Choosing a liquid flow meter for a particular application requires knowledge of

- installation requirements (flange, tap, straight length, pipe size, etc.),
- accuracy required,
- fluid type and its properties including temperature, density, pressure, viscosity, cleanliness of the fluid (turbidity), corrosiveness, and levels of aeration,
- flow conditions the meter is to encounter including the range of expected flow velocities and flow profile and turbulence at the point of measurement,
- pressure drop limitations,
- and available budget.

In general, flow sensors can be grouped into four different meter types:

- obstruction differential pressure-type flow meters (e.g., nozzle, orifice plate meter, venturi meter, averaging pitot tube meter, wedge, flow tube),
- obstruction sampling-type flow meters (e.g., variable-area meter, positive displacement meter, turbine meter, tangential paddle-wheel meter, target meter, vortex meter, insertion magnetic meter, hot-wire anemometer),
- non-interfering meters (e.g., ultrasonic meter, full bore magnetic meter),
- and mass flow meters (e.g., coriolis mass flow meter, angular momentum mass flow meter).

While there are specific applications for each of these metering technologies, this clause discusses the more common liquid flow measurement devices that are used in conjunction with temperature measurements to determine the thermal energy in a fluid flow. Obstruction differential pressure-type flow meters will not be discussed due to the extensive availability of literature on this subject.

A1.5.1 Nondifferential Pressure Obstruction Flow Meters. Several types of nondifferential pressure obstruction flow meters have been developed that are capable of providing a linear output signal over a wide range of flow rates, often without the severe pressure-loss penalty that is incurred with an orifice plate or venturi meters. These include the variable-area meter, positive displacement meter, axial turbine meter, tangential paddle-wheel meter, target meter, vortex meter, and insertion magnetic meter. In general, these meters place a small target, weight, spinning wheel, or sensor in the flow stream that then allows the velocity of the fluid to be determined. These instruments must be calibrated and installed with care to ensure that the sampled flow velocity can be accurately related to the average flow velocity.

A1.5.1a Axial Turbine Meters. Axial turbine meters measure fluid flow by counting the rotations of a rotor that is placed in a flow stream. Axial turbine meters can be full bore-type or insertion-type. Full-bore turbine meters have an axial rotor and a housing that is sized for a specific installation. Turbine insertion meters allow the axial turbine to be inserted into the fluid stream and use the existing pipe as the meter body. This type of meter can be hot-tapped into existing pipes through a valving system without having to shut down the system.

The insertion turbine meter may have one or two turbines. The single turbine only samples the fluid velocity at a small cross-sectional area of pipe; therefore, total volumetric flow rate can only be accurately inferred if the meter location provides conditions consistent with the meter's calibration. This is typically in fully developed and stable flow conditions with minimal nonrotational or skewed components. Manufacturer specifications rely on these conditions being provided. These conditions are typically found in long straight sections of pipe removed from internal turbulence.

One dual turbine insertion meter offers the advantage of counter-rotating turbines, thereby reducing the impacts of rotational flow while increasing the cross-sectional area sampled. Insertion meters can be used on pipe above 5 cm (2-inch) diameter with very low pressure loss. The rate of rotation of the turbine, driven by the fluid, provides an output linear with flow rate. This output can usually be obtained either as a signal pulse representing a quantity of fluid flow or as a frequency or analog signal proportional to flow rate.

A1.5.1b Vortex Meters. Vortex meters utilize the same basic principle that makes telephone wires oscillate in the wind between telephone poles. This effect is due to oscillating instabilities in a low field after it splits into two flow streams around a blunt object. Vortex meters have no moving parts and are suitable for gas, steam, and clean liquid flow measurements. They require minimal maintenance and have good accuracy and long-term precision. Vortex meters provide a linear digital (or analog) output. They are a point measurement and need to be calibrated.

A1.5.1c Insertion Magnetic Meters. Insertion magnetic meters utilize Faraday's Law of electromatic induction to facilitate the measurement of sampled flow. Insertion magnetic meters can be found with single or multiple sensors per probe. Greater accuracy can be obtained if multiple probes are used at each measurement location. They require an electrically conductive fluid.

A1.5.2 Non-Interfering Flow Meters. In all of the previously mentioned meters, some interference with the flow stream was necessary to extract a measurement. Recently, a relatively new class of meters has been developed that are able to extract a measurement without placing an obstruction into the fluid stream.

A1.5.2a Ultrasonic Flow Meters. Transit-time ultrasonic flow meters measure fluid velocities by detecting small differences in the transit time of sound waves that are shot at an angle across a fluid stream. Various designs have been developed that utilize multiple pass, multiple path configurations. Clamp-on ultrasonic flow meters have been developed that now facilitate convenient measurement of fluid velocities in pipes of varying sizes. Typical manufacturers' stated accuracies vary from 1% to 3% of actual flow to 2% of full scale. The ability to achieve these accuracies is largely dependent upon installation technique and field conditions.

Doppler ultrasonic flow meters measure fluid velocities by sensing the velocity of small particles or air bubbles entrained in the fluid with sound waves that are shot at an angle across a fluid stream. Such meters require a certain amount of particles and air bubbles in the fluid to reflect the signal back to the receiver. Doppler-effect meters are available with accuracy between 2% and 5% of full scale and are normally less expensive than the standard transit time-effect ultrasonic devices. Meter cost is independent of pipe size.

It should be noted that ultrasonic flow meters are difficult to field calibrate. These meters are velocity-dependent devices and are highly vulnerable to errors caused by poor pipe and flow conditions and improper installation technique, as are the obstruction types of flow meters. Using the manufacturer's stated accuracy for field applications can be risky.

A1.5.2b Full-Bore Magnetic Meters. Full-bore magnetic flow meters utilize Faraday's law of electromagnetic induction to measure the average flow velocity in a pipe. Magnetic coils surround the flow, utilizing a pulsed DC or AC generated field to produce a signal. The signal is proportional to the average velocity in the pipe and is nearly unaffected by flow profile. Manufacturers of pulsed DC excited magnetic flow meters have a stated flow uncertainty of 1% within a 10:1 turndown if flow velocity is greater than 0.5 ft/s. AC excited magnetic flowmeters have a stated flow uncertainty of 1% to 2% full scale. They require an electrically conductive fluid.

Magnetic meters are becoming the flow meter of choice for custody transfer energy based liquid flow measurement. They offer many advantages such as 0.25% to 1% accuracy, high precision, and wide operating ranges under limited restrictions at increasingly reduced costs. Advancements in approaches, such as pulsed DC and dual frequency excitation, offer excellent long-term stability and greatly reduce the need for recalibration. Full bore magnetic flow meters come in a variety installation formats. While they are very accurate, they are also somewhat expensive.

A1.5.3 Minimum Installation Requirements.

A1.5.3a Location Specification. Flow meters that are sensitive to flow conditions (dynamic flow, severe rotational velocities, or high spatial variation in velocities) should be provided at a minimum 20 diameters upstream and 10 diameters downstream of straight-run piping, clear of any flow disturbances. More than 20 diameters of upstream straight run piping are preferred if multi-plane close coupled elbows are present upstream. If insertion type flowmeters are utilized, the hot tap should be oriented in the plane of outside radius of first upstream elbow.

A1.5.3b Use of Flow Straightening Devices. If the minimum installation requirements cannot be met or severe flow conditions exist, a flow-straightening device should be employed.

A1.6 Air Flow. Air flow is measured with many of the same measurement techniques as liquid flow. Sensor selection is also dependent upon the measurement application, although cooling coil face velocity, fume hood ventilation air flow, and compressed air flow may all be measured by the same sensor type. Air flow offers an even greater challenge than liquid due to the extensive size or lack of a clearly defined cross-sectional area. Also prevalent are unpredictable flow profiles, low velocities, and the presence of moisture that complicate the measurement.

Typical sensor types include the pitot tube, rotameters, and vane and hot wire anemometers. Pitot tubes can be single port or multiple port. Hot wire anemometers and pitot tubes can be employed in area averaging arrays to obtain a more accurate measurement in fume hood and duct applications. Some sensor systems incorporate upstream flow-straightening vanes. Orifice plates and nozzles are also used, especially in industrial applications. Pitot tubes, orifice plates, and nozzles utilize a differential pressure transducer or transmitter across the sensor to interpret the measured flow velocity. To determine mass flow, the pressure and temperature also need to be recorded.

A1.7 Steam Flow. Steam flow is also measured with many of the same techniques as liquid flow. Orifices, averaging pitot tube, vortex shedding, and nozzles (the most common) are the more common sensor types. The insertion turbine provides for greater rangibility than vortex shedding but is highly vulnerable to the destructive forces of liquid condensate that may be present during start-up. Nozzles are probably the most accurate, but at higher temperatures, their accuracy declines. Orifices usually provide adequate accuracy, and their pressure drop is not too bad with steam, though it may still be undesirable. Their turndown is also undesirable. Hot wire anemometers have a good turndown, but they should be used only when the steam is superheated. Actually, none of the meters can measure actual flow rate for wet steam, unless the steam quality is known. Averaging pitot tubes may be easier to install than orifices, but they are less accurate and there is a risk of plugging. Vortex shedding has a better turndown ratio than either the annubar or orifice, although it is probably less accurate than the orifice.

A1.8 Thermal Flow

A1.8.1 Thermal Product Energy Use Measurements. Thermal product energy use measurements refer to measurements taken after the energy fuel (e.g., electricity, natural gas) has been converted into thermal energy (e.g., hot water or chilled water), for example, hot water for heating, potable domestic hot water for human use, chilled water, and steam. It is recommended that such energy use measurements be designated separately (i.e., Btu, t or Joule, t) from energy fuel measurements (i.e., Btu, f or Joule, f) since the thermal product energy use measurements do not include the conversion efficiency.

Thermal product energy use measurements usually require a volumetric flow rate per unit time (m), a specific heat constant (e.g., at constant pressure [cp]), and a temperature difference (delta-T) (it would also need density if it is steam or air). Accurate thermal energy use measurements usually require calibrated flow meters such as axial turbine meters, tangential paddle-wheel meters, target-type meters, pitot tubes, orifice meters, venturi meters, ultrasonic meters, magnetic meters (Miller 1989), specific heats for the fluid being measured (e.g., water, antifreeze), and usually temperature measurements for the supply and return temperatures (assuming a loop configuration) or temperature rise measurements (for domestic water heaters).

One method of recording the thermal product energy use (e.g., the cooling provided by the building chillers) is with the use of a Btu meter. A Btu meter, either a stand-alone device or a "virtual" Btu, t meter as part of a larger meter/recorder device, performs an internal Btu, t calculation in real time based on inputs from a flow meter and supply and return temperature sensors. With a stable specific heat constant and accurate sensors, these electronic Btu meters offer accuracy better than 3%. They are most attractive on larger or more critical installations where accuracy is a prime concern. A side benefit is the availability of real-time operating data such as flow rate, temperature (both supply and return), and thermal rate. Many also offer totalization.

When measuring the narrow differential temperature (T) range typical of chilled water systems, the two temperature sensors should be matched or calibrated to the tightest tolerance possible. For the purpose of computing thermal loads in Btu per hour or tons of refrigeration, it is more important that the sensors be matched or calibrated with respect to one another than for their calibration to be traceable to a standard. Attention to this detail will maximize the accuracy of the Btu computation. Suppliers of temperature sensors can provide sets of matched devices when ordered for this purpose. Typical purchasing specifications are for a matched set of RTD assemblies (each consisting of an RTD probe, holder, connection head with terminal strip, and a stainless steel thermowell), calibrated to indicate the same temperature within a tolerance of 0.15°F over the range 25°F to 75°F. A calibration data sheet should be provided with each set.

Thermal energy use measurements for steam can require steam flow measurements (e.g., steam flow or condensate flow), steam pressure, temperature, and feedwater temperature where the energy content of the steam is then calculated using steam tables. In instances where the steam production is constant, this can be reduced to measurements of steam flow or condensate flow only (i.e., assumes a constant steam temperature-pressure and feedwater temperature-pressure).

A1.8.2 Thermal Fuel Energy Use Measurements. Thermal fuel energy use measurements refer to measurements of the fuel that is being consumed by the energy conversion device, including coal, wood, biomass, natural gas, oil, and various forms of liquid petroleum. For any of the fuel types, the higher heating value of the fuel must be known. These values are usually measured by the fuel supplier or can be obtained by sending a sample of the fuel for analysis. The thermal fuel energy use is then calculated by multiplying the mass (i.e., kg or lb) of the fuel times the higher heating value. Natural gas delivered at varying temperature and pressures may need to be compensated. Coal weight or gallons of oil may need to be obtained from shipping invoices.

A1.9 Pressure. Selecting a pressure measurement device for an application entails consideration of

- the accuracy and stability required,
- pressure range,
- the reference pressure (gage, absolute, or differential),
- the desired signal output (0-5 vdc, 4-20 ma, digital),
- special features of the device's electronics, such as flexibility of scaling, digital communications/remote access, or fast response,
- ease of use,
- and the available budget.

For industrial applications, the main categories of pressure measurement instruments include

- manometers,
- local indication, gage type,
- transducers,
- and transmitters.

Each category includes many different mechanical designs. This clause discusses the more common designs and the applications for which they would be useful.

A1.9.1 Manometers. The most common types of manometers include visual (U-tube, well, inclined, and micro) and digital/electronic (float, capacitance, sonar detector). They can handle static or differential pressure spans from 0.1 inch to about 60 psid, with a maximum design pressure of about 6000 psig. Visual manometers can be read to about 0.01 inch and micromanometers can be read to about 0.002 inch. Manometers are most useful for temporary instrumentation setups when readings are to be taken manually. They are fundamental instruments and do not require independent calibration equipment, since they can be zeroed manually. For improved accuracy, their readings should be adjusted for temperature and gravity to standard conditions. Accuracy is also affected by capillary effects in the tube and by the method used to read the liquid level.

Since manometers rely on a liquid level, they are sometimes difficult to read if the pressure is not steady because the liquid level will oscillate. They are less suitable for obtaining accurate readings under unsteady conditions. They also require some maintenance to keep them clean so that they can be read easily and so that their inner diameter (ID) does not change and to keep them free of air bubbles. It is very important to make sure all air is bled out of the whole instrument system when they are used. There are also safety issues that need to be considered, since manometers can break or their fluid (sometimes mercury) can blow over into the process or leak into the environment. Visual manometers cost between one and several hundred dollars, while higher tech NIST traceable digital manometers cost $2,000 to $3,000.

The main advantages of manometers are their high accuracy, low cost, and simplicity. Their accuracy is based on how accurately they can be read and by the adjustments that are made to standard conditions. There are some safety concerns, as well as maintenance requirements.

A1.9.2 Gages. The most common types of pressure indicating gages include bellows, Bourdon tube, and diaphragm designs. They are available in many ranges, from vacuum to 10,000 psig. Dial sizes can vary from 2 to 6 inches. The accuracy tends to vary with dial size, ranging from 0.25% for large dials to 2% for small dials. These instruments are easier to set up and use than manometers, but because they are not "fundamental" instruments, they may need calibration if accuracy is required. Accuracy can be affected by temperature, as well as mechanical damage due to corrosion or vibration. Some gages are filled with glycerin to dampen the vibration of the pointer and to eliminate condensation within the gage.

As with other pressure measurement devices, it is important to bleed the instrument lines of air, in order to maintain a known water leg up to the gage. Gages should be mounted in the same position that they were calibrated in to maintain accuracy. Because they are usually installed in a vertical position, air may tend to collect below the gage, which would affect its water leg correction and the accuracy of the reading. If they are to be used with corrosive liquid or vapor, they should be isolated from the process with a seal (e.g., chemical, diaphragm, or volumetric) or purge. Pointers can be fitted with a maximum pointer to indicate the maximum pressure reached in the system. Costs for gages range from less than a hundred to several hundred dollars for more accurate instruments.

The advantages of gages are their low cost and simplicity. The disadvantages are that they need to be read manually and they need calibration for good accuracy.

A1.9.3 Pressure Transducers. These pressure measurement devices come in a variety of types, including strain gauge, capacitive, potentiometric, piezoelectric, and optical. Most of these types can measure pressures from somewhere in the vacuum range to at least 10,000 psig. The potentiometric and optical are not designed to measure vacuum. Most can be accurate to 0.1% of span or to 0.25% of full scale, but the piezoelectric and potentiometric may be accurate to 0.5% to 1.0% of full scale. To obtain 0.1% accuracy, transducers should be calibrated. They are also affected by temperature, and their readings would need to be corrected in order to maintain accuracy to better than 0.1%. Temperature is typically compensated for in the more "intelligent" transmitter designs (discussed in A1.9.4).

The most popular designs are the strain gauge and capacitive types. Transducers (without transmitters) typically need signal conditioning to amplify their output for measurement by a data collection system. They are less expensive than transmitters (several hundred dollars for strain gage types). They usually respond faster to pressure fluctuations than transmitters but are less flexible in terms of being able to adjust their spans and output, and they do not compensate their output for temperature or static pressure (which can affect differential pressure transducers). They are better than manometers and dial gages for long-term installations or where a large number of measurement points need to be recorded and linked to a data measurement system.

A1.9.4 Transmitters. Most transducer types described in A1.9.3 are available with either a conventional or "intelligent" transmitter. Conventional transmitters condition the output of the transducer and typically provide a 4 to 20 mA output signal. They usually have potentiometers for zeroing and ranging. The more "intelligent" transmitter also provides adjustments to the output signal for temperature and static pressure (for some differential pressure transmitters). The output signal can be made proportional to the square root of the pressure. Transmitters can also provide filtering of the output signal, to reduce the noise in the reading (by providing a running average for output). An "intelligent" transmitter can be communicated with remotely, to perform such things as diagnostics, resetting, rescaling, or calibration. Some can also transmit data digitally, over a single twisted-pair cable that can handle more than one sensor output.

Like pressure transducers, pressure transmitters should be calibrated in order to attain accuracies of about 0.1%. However, they will maintain their accuracy over a wider range of conditions because of their temperature (and pressure) compensation. They are more expensive (in the $1,000 range), but they are easier to use with a data collection system and more convenient to configure, calibrate, and maintain.

A1.9.5 Minimum Installation Requirements. In order for static pressure measurements to be accurate, instrument taps should located on straight piping runs, and they should be smooth, with no burrs, along the inside of the pipe. Instrument tubing should slope downward to the sensor location where the lines will fill with liquid, so that air (or vapor) can rise out of the tubing. ASME Performance Test Code guidelines recommend 1/2 inch tubing, but many installations use 1/4 inch tubing for convenience. Where the reading's accuracy can be significantly affected by air in the tubing (such as differential pressure measurements under a vacuum), larger tubing and shorter, steeper tubing runs, are recommended, if possible. For vacuum measurements of vapor, the tubing should slope upward to the sensor location, so that condensate can drain out of the tubing toward the process. Sometimes a very small air bleed can maintain a clear line without affecting the measurement. Transmitters should be conveniently located to allow for calibration and maintenance.

Pressure sensors should be mounted as recommended by the manufacturer (usually horizontally for many transducers and transmitters or vertically for gages and manometers) with enough rigidity to minimize vibration, which could affect reading accuracy and damage equipment. If necessary, the process should be isolated from the sensor to avoid corrosion. Dampeners may be used to reduce significant pressure fluctuations. Bleed lines should be installed to enable convenient bleeding of air out of the sensor lines, up to the sensor. Some sensors are equipped with bleed plugs on their bodies. On the most critical measurements (such as fuel flow), consider redundant sensors, to improve accuracy and reliability.

A1.10 References

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A2 Calibration Techniques

A2.1 Published Procedures. For the highest quality measurements, it is recommended that the calibration procedures developed by national or international standards organizations such as the National Institute of Standards and Technology (NIST) be used. A list of calibration procedures is provided in the references and includes Baker and Hurley (1984), EEI (1981), Huang (1991), Hyland and Hurley (1983), Hurley and Schooley (1984), Hurley (1985), ISA (1976), Kulwicki (1991), and Ramboz and McAuliff (1983).

A2.2 Calibration Methods by Measurement Type and Rigor. For those situations where standard methods are not available (insertion flow, for example) or are poorly applied in the field or where new technology is now available, the following is provided to assist the user.

A2.2.1 Temperature

a. Single-point verification/calibration in the field using physical standards: ice bath, 32°F; gallium cell, 84.59°F.

b. Multi-point verification/calibration in the field at various points in the operating range (including minimum, typical, and maximum) utilizing a Dewar flask; include physical standards whenever possible.

c. Laboratory and field multi-point verification/calibrations using cold block, hot block cell, or regulated fluid bath that has been calibrated by a NIST traceable device or utilizes a secondary standard as reference; include physical standards whenever possible.

A2.2.2 Relative Humidity

a. Single-point calibrator, 3% (which has been calibrated by a NIST traceable device).

b. Portable environmental chamber that has been lab calibrated with a NIST traceable dew-point monitor, 3%.

c. Laboratory calibration in a salt bath or in an environmental chamber controlled by a calibrated NIST traceable dew-point monitor, 3%. Salt baths are not recommended outside of the laboratory. They do not transport well and their accuracy is greatly affected by the unstable environmental conditions usually found in the field. Field calibration using a single-point calibrator or portable environmental chamber that has been lab calibrated with a NIST traceable dew-point monitor (Turner et al. 1992).

A2.2.3 Fluid Flow. Field calibrations of flow measurement systems are both complex and costly. Use of portable ultrasonic flow meters (UFMs) to calibrate a permanent liquid flow meter is not recommended. Their use as a transfer standard to known accuracy requires sophisticated procedures that are extremely expensive and time consuming to apply. The accuracy of a single measurement is highly suspect but they are very helpful in establishing the flow profile within the pipe. UFMs are velocity-dependent devices and are highly vulnerable to variations in flow profile and installation error. They should be considered 5% devices at best for pipe diameters 12 inches and under. UFM flow profile compensation assumes a fully developed flow profile at the calculated Reynolds number. Even at 10 diameters downstream of an elbow, significantly altered flow profile will occur. It is suggested that flow profile compensation be turned off and the acceptable deviation between the measuring flow meter and the UFM be restricted to 5% for applications with less than 10 pipe diameters of straight length pipe upstream of the UFM.

Since field calibrations can be difficult and expensive, it is recommended that an appropriate device be selected that is the least vulnerable to field conditions. It should provide the accuracy required and be laboratory calibrated. If the device selected is vulnerable to field conditions, as much effort as possible should be given in providing it with stable flow conditions in the field. In long- term monitoring applications, the device should be inspected and cleaned and provided with laboratory recalibration on a periodic basis. In lieu of field calibrations, the flow profile should be thoroughly documented and alternative measures used to ensure the accuracy of the measurement point. For differential pressure devices, the associated differential pressure (and pressure if measuring vapor state) instrumentation should be calibrated periodically.

A2.2.3.1 Fixed Flow Applications

a. Spot check flow utilizing a portable ultrasonic flow meter.

b. Verify flow profile utilizing a portable ultrasonic flow meter. See method below.

c. (1) Install flow tube that produces constant flow conditions and has been calibrated in a laboratory with NIST traceable instrumentation and methods.

(2) Multi-plane pitot tube traverse (this can be done in most applications).

A2.2.3.2 Variable Flow Applications

a. Spot check flow utilizing a portable ultrasonic flow meter at a range of flow conditions.

b. Verify flow profile at minimum, typical, and maximum conditions utilizing a portable ultrasonic flow meter. See method provided below in A2.2.3.3.

c. (1) Install flow tube that has been calibrated in a laboratory with NIST traceable instrumentation and methods under similar flow conditions as found in the field.

(2) Multi-plane pitot tube traverse at a minimum of five conditions across the range.

A2.2.3.3 Evaluation of Spatial Variation in a Liquid Flow Profile

a. *Introduction.* One method to field-verify the accuracy of an installed flow sensor is to confirm that the installed flow conditions in the field are consistent with the flow conditions that existed during laboratory calibration. If the laboratory calibration was done properly, the flow sensor was calibrated under flow conditions that provided centered and stable flow conditions over the range of flow velocities the sensor would see when installed. If the flow profile at the point of measurement is centered and stable, the laboratory calibration can be considered to apply to the field installation. One method of verifying that the flow stream is centered and stable is to evaluate its spatial variation.

b. *Method.* Spatial variation can be determined by sampling the flow profile at a number of radial points across the pipe cross-section at the measurement location with one channel of a two-channel ultrasonic flow meter. The second channel is required as a control to correct the sample average due to variations of flow in time. The suggested method using an ultrasonic flowmeter to determine spatial variation uncertainty is as follows:

1. Use a two-channel ultrasonic flow meter system whose function has been verified by an independent laboratory, other than the manufacturer.

2. At the proposed measurement location:

(a) Determine pipe parameters: diameter, wall thickness, material, temperature, presence and condition of lining.

(b) Determine fluid parameters: temperature, sonic velocity, viscosity.

(c) With channel one, take flow readings at orientations of 0, 45, 90, and 135 (from the top of the pipe on horizontal pipes) while simultaneously taking readings with channel two at 90 nearby.

(d) Use the reflect (two-path) mode. If the flow meter has a flow profile compensation feature, this compensation should be turned off.

(e) The flow profile should be verified at least at the minimum, typical, and maximum expected flow rates.

3. The ultrasonic flow meter is an excellent diagnostic tool, useful for identifying variations in the flow profile. But using the ultrasonic flow meter's average measured flow as a calibrated flow reading is not recommended. This requires a sophisticated procedure outside the scope of this annex.

4. Spatial variation for each expected flow rate can be calculated as follows:

Spatial Variation, % = (t statistic) × (standard deviation of measurements corrected for variations due to time) / (number of measurements)$^{1/2}$/(average of the corrected measurement) × 100.

5. For dynamic applications that yield multiple ranges of typical flow rates, spatial variation is then equal to the standard deviation of the spatial variations for each expected flow rate (such as minimum, typical, and maximum expected) divided by the square root of the number of expected flow rates observed. It is also possible to weight each expected flow rate by the expected frequency of occurrence.

This procedure was developed for *ANSI/ASHRAE Standard 150, Method of Testing the Performance of Cool Storage Systems*. A sample calculation is found in its Annex D, "A Method of Determining Spatial Variation in a Liquid Flow Stream" (ASHRAE 1997).

A2.2.4 Air Flow. Calibration of air flow measurement systems in the field is often more difficult than for liquid flow because of large and complex ductwork and the difficulty of using clamp-on ultrasonic instrumentation to measure air flow. While ultrasonics can be used to determine flow profile of liquid flows, with great care for calibration, the clamp-ons have a poor coupling to the flow if used with air. Whether or not a calibration should be performed depends on the installed flow system. If the flow system is inherently accurate, such as an array of pitot tubes or a flow nozzle or orifice with adequate flow conditioning, then inspection of the array for damage or deposits and a calibration of the differential pressure (DP) sensor should be adequate. The DP and pressure sensors should be calibrated periodically, such as every six months to one year if high accuracy is required. If the flow metering system has greater potential inaccuracy, then a field calibration may be necessary (e.g., if the system cannot be sent to a calibration laboratory).

Field calibrations of air flow can be performed under steady-state conditions by pitot tube or propeller anemometer traverses in at least two planes. These devices require laboratory calibration for the field calibration to be valid. Where the field conditions will vary under normal operation, calibrations should be checked over a range of at least five flow rates.

If the flow measurement accuracy is not critical, a rough check can be made by performing a flow and/or an energy balance with another system that has good flow measurement instrumentation.

A2.2.4.1 Fixed Flow Applications

a. Inspect flow meter for damage, deposits, or plugging, and repair if necessary. Calibrate DP and static pressure instrumentation.

b. Check flow by performing a flow or energy balance with other measurements.

c. Perform a multi-plane pitot tube or anemometer traverse at the expected flowrate.

A2.2.4.2 Variable Flow Applications

a. Inspect flow meter for damage, deposits, or plugging, and repair if necessary. Calibrate DP and static pressure instrumentation.

b. Check flow by performing a flow or energy balance with other measurements under several flow conditions.

c. Perform a multi-plane pitot tube or anemometer traverse under at least five flow conditions across the range of expected flows.

A2.2.5 Pressure. The accuracy to which pressure-sensing instrumentation is to be calibrated depends on the required accuracy of the process measurement. For example, differential pressure and pressures used to determine flow rate typically require the highest accuracy; pressures used to determine state point require good accuracy; pressures used by operations for checking processes may require less accuracy. The frequency of the calibration will depend on the stability of the instrumentation and the accuracy requirements. For very high accuracy, a calibration at installation and every six months to one year is recommended. For good accuracy, calibration at installation and then every two years may be sufficient. For less accuracy, a loop test at installation and then a calibration when there appears to be a problem should suffice.

The most accurate calibration would entail a through-system calibration, where a known pressure is maintained at the transmitter and compared with the reading at the DCS or digital readout. It is preferred that the transmitter be calibrated after it is mounted and installation is complete. Where a "smart" transmitter communicates digitally with a control system, it may be possible to take the reading at the transmitter, although a through-system calibration is still the preferred method.

The pressure source for the calibration can be a dead weight tester or an electronic pressure calibrator for ranges above atmosphere or an accurate digital pressure gage for ranges below atmosphere. The accurate calibration should cover the entire expected operating pressure range of the process, with at least five calibration points. The correction can be applied either within the sensor or in the control system. After the correction is applied, another set of calibration points should be run to check that the correction was applied properly. A record of calibrations for each instrument should be maintained. If after several calibrations, the drift is found to be very small, then the calibration interval can be increased.

The reference pressure should be adjusted for temperature, local gravity, and static pressure if required by the dead weight tester or electronic calibrator. These adjustments correct the reading to reference conditions, such as 20°C or the acceleration of gravity at 45° latitude at sea level. The adjustments should be made to the reference pressures before the calibration corrections are applied to the instrument.

A2.2.5.1 Static Pressure. Gage pressure calibrations can be performed with dead weight testers (inaccuracies are less than 0.05%) or electronic pressure calibrators (inaccuracies are about 0.1%). If the pressure sensor is set up to read absolute pressure, an atmospheric pressure gage will be needed in order to add ambient pressure to the applied reading. Calibrate at a minimum of five points, including the low and high ends of the instrument range. Depending on what the data system accepts, the corrections could be a linear curve representing the calibration points that encompass the expected process readings, or if all five calibration points are reasonable, they can be entered in the data system as discreet points.

Vacuum range pressures can be attained with a vacuum pump, with an atmospheric pressure gage as the reference. Draw a vacuum on the transmitter. Use a 0 to 1000 micron vacuum gage to verify that 0 psia has been reached, if it is one of the calibration points. Zero the reference gage if necessary. Gradually bleed air into the system. At each calibration point, stop the bleed and record the calibration data.

A2.2.5.2 Differential Pressure. Differential pressure transmitters are calibrated by applying a known pressure to their high-pressure side. Pressure can be applied by a dead weight tester or electronic calibrator. The calibration results are applied in the same way as for static pressure transmitters. This method of calibration is acceptable for high line pressure applications if the transmitters have static pressure compensation. If the transmitters do not compensate for line pressure, and high accuracy is required, the calibration source can be a special dead weight tester that applies both a differential pressure and a static pressure. If the line pressure is predictable, the differential pressure calibration points can be applied at a single static pressure. If the static pressure varies, the calibration points can be applied at a range of static pressures, and the calibration corrections can be interpolated.

A2.2.5.3 Very Low Differential Pressure. Very low differential pressure instruments (such as draft range transmitters) can be calibrated in comparison to a very sensitive manometer, such as a micromanometer or digital manometer. The manometer must be zeroed. A hand pump/bleed valve setup can be used to apply the small pressures required to the high sides. The manometer is adjusted and the instrument readings are compared at each point. The temperature of the manometer fluid should be used to adjust its readings to the standard temperature conditions of the transmitter.

A2.2.6 Btu Meters. See ANSI/ASHRAE Standard 125.

A2.3 References

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A3 Laboratory Standards for Measurement of Physical Characteristics

Annex A3 provides an annotated bibliography of currently available laboratory standards for measurement of physical characteristics that might be required as part of the determination of energy or demand savings. While laboratory standards focus on the use of laboratory test equipment and are not always readily transferable to field measurement, they provide guidance as to measurement techniques. Measurement types listed include electrical power, electrical current, electrical voltage, temperature, liquid flow, air flow, hydraulic pressure, air pressure, and thermal energy. A description of potential measurement instrumentation is provided in Annex A1.

A3.1 Power

ANSI C12.1 - 1988, American National Standard Code for Electricity Metering. ANSI C12.1 establishes acceptable performance criteria for new types of AC watt-hour meters, demand meters, demand registers, pulse devices, instrument transformers, and auxiliary devices. It states acceptable in-service performance levels for meters and devices used in revenue metering. It also includes information on related subjects, such as recommended measurement standards, installation requirements, test methods, and test schedules. The general discussion of the measurement of power, energy, and power factor is informative. The standard is not a how-to manual for electricity metering but stresses the performance criteria required for revenue metering.

Other relevant test standards include:

ASME PTC 19.6 -1955, Electrical Measurements in Power Circuits.

A3.2 Temperature

ANSI/ASHRAE 41.1-1986 (RA 91), Standard Method for Temperature Measurement. ASHRAE Standard 41.1 describes procedures intended specifically for use in testing HVAC equipment and components. The standard applies to temperature measurements in air, water, brine, and volatile or nonvolatile refrigerants under both steady-state and transient conditions between –40°F and 400°F (–40°C and 204°C). This standard has general measurement techniques as well as specific techniques for liquid-in-glass thermometers, thermocouples, and electric resistance thermometers (including thermistors). Recommended accuracy, precision, and test tolerances are given for air dry-bulb, air wet-bulb, water, and refrigerant temperatures. Limits of error of thermocouples and extension wires are given for different types of thermocouples. The general guidelines of this standard apply to field and laboratory measurements, while the accuracy recommendations need to be compared to the requirements for field performance testing. Investigations are required to test if the accuracy recommendations can be achieved at reasonable costs in field applications.

ANSI/ASME PTC 19.3-1974 (R1985), Temperature Measurement. ASME Performance Test Code 19.3 is a summary discussion of temperature measurement and basic sources of error for radiation thermometers, thermocouples, resistance thermometers, liquid-in-glass thermometers, and others. The code goes into greater detail than ASHRAE 41.1 on the theory and principles of operation, materials of construction, and characteristics of the various types of thermometers. The limits of error for thermocouples listed in the two codes are identical. PTC 19.3 details extensive laboratory calibration methods for the various types of thermometers. While this code is an excellent reference, it has limited application and installation details that could apply to in-situ measurements. The standard includes a list of advantages and disadvantages for each type of thermometer, which could be helpful in choosing measurement techniques for particular projects.

A3.3 Liquid flow

There are several applicable standards for liquid flow measurement depending on the instrumentation. In each case, the standard describes procedures and techniques for the specific class of instrumentation. The following standards may be appropriate for in-situ flow testing. The main criteria for field applications are accuracy, cost, installation and retrieval methods, ease of measurement, and degree of intrusion.

ANSI/ASHRAE 41.8-1989, Standard Methods of Measurement of Flow of Liquids in Pipes Using Orifice Flowmeters.

ANSI/ASME MFC-2M-1983 (R1988), Measurement Uncertainty for Fluid Flow in Closed Conduits.

ANSI/ASME MFC-5M-1985 (R1989), Measurement of Liquid Flow in Closed Conduits Using Transit-time Ultrasonic Flow Meters.

ANSI/ASME MFC-6M-1987, Measurement of Fluid Flow in Pipes Using Vortex Flow Meters.

ANSI/ASME MFC-8M-1988, Fluid Flow in Closed Conduits—Connections for Pressure Signal Transmission Between Primary and Secondary Devices.

ANSI/ASME MFC-9M-1988, Measurement of Liquid Flow in Closed Conduits by Weighing Method.

ANSI/ASME MFC-10M-1988, Method for Establishing Installation Effects on Flowmeters.

ANSI/ASME MFC-11M-1989, Measurement of Fluid Flow by Means of Coriolis Mass Flowmeters.

ASME PTC 19.5-1972, Part II of Fluid Meters—Interim Supplement on Instruments and Apparatus.

A3.4 Air flow

ANSI/ASHRAE 41.2-1987 (RA92), Standard Methods for Laboratory Airflow Measurement. ASHRAE Standard 41.2 sets forth recommended practices for airflow measurement for consistency in procedures and for reference in other ASHRAE standards. The standard describes procedures to calculate flow rates from measurements of pressure differential across a flow nozzle or from measurements of velocity pressure obtained by a pitot traverse. The general practices outlined in this standard apply to both laboratory and field measurement of air flow. The obtainable accuracies can be used to help determine if the techniques in this standard are appropriate for a particular application.

A3.5 Pressure

ANSI/ASHRAE 41.3-1989, Standard Method for Pressure Measurement. ASHRAE Standard 41.3 presents practices for accurately measuring steady-state, nonpulsating pressures. The scope of the standard covers type of pressure, range of applications, accuracy, and installation and operation techniques. Devices covered include differential pressure (head) meters, elastic element gages, manometric gages, pressure spring gages, and pressure transducers. The limits of accuracy and calibration techniques for these devices are discussed. Examples of measurement applications for HVAC ductwork and hydronic systems are given. Once the required pressure measurement accuracies are determined, this standard can be utilized to help choose appropriate pressure measuring devices.

ANSI/ASME PTC 19.2-1987, Pressure Measurement Instruments and Apparatus. ASME Performance Test Code 19.2 describes the various types of instruments and methods of measurement likely to be prescribed by other codes and standards. Details that will determine their range of application are given, such as the limits and sources of error, methods of calibration, and precautions. Static, differential, absolute, gage, and velocity pressure are defined. Guidelines for pressure connections to systems are detailed, along with potential sources of error. For liquid level gages, tables are supplied for corrections due to meniscus height, capillary depression, temperature, and gravity variations. Other types of instruments described are deadweight gages, elastic gages, and low-pressure measurement devices.

Modera, M. 1993. Field comparison of alternative techniques for measuring air distribution system leakage. Lawrence Berkeley Laboratory Report, LBL-33818.

A3.6 Thermal Energy

ANSI/ASHRAE 125-1992, Method of Testing Thermal Energy Meters for Liquid Streams in HVAC Systems. ASHRAE Standard 125 provides a method for testing factory-assembled thermal energy meters used to measure the thermal energy added to or extracted from a liquid stream supplying an HVAC system. The accuracy and precision requirements of temperature and flow measurements and test procedures are given in order to create plots of thermal meter error as a function of flow and temperature difference. This type of meter has clear applications for chiller testing, if they prove to be accurate in in-situ situations.

A4 Equipment Testing Standards

A4.1 Equipment Testing Standards: Chillers

The theoretical aspects of calculating chiller performance are well understood and documented. Chiller capacity and efficiency are calculated from measurements of water flow, temperature difference, and power input (Figure A4-1).

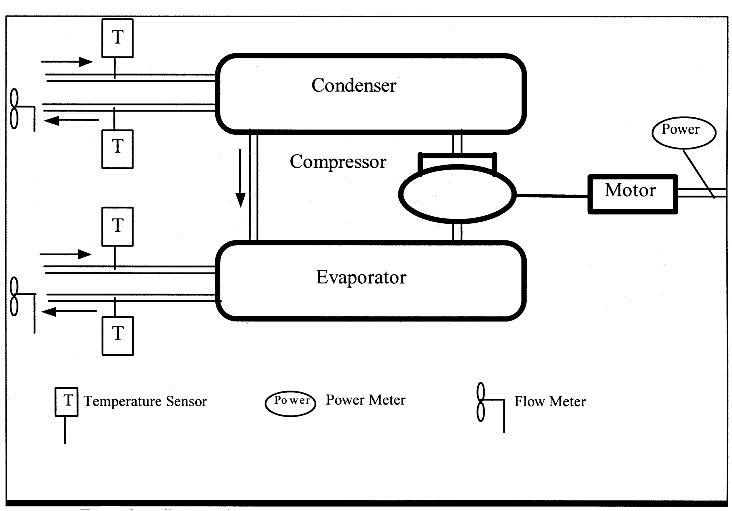

Figure A4-1 Typical chiller with minimum required instrumentation.

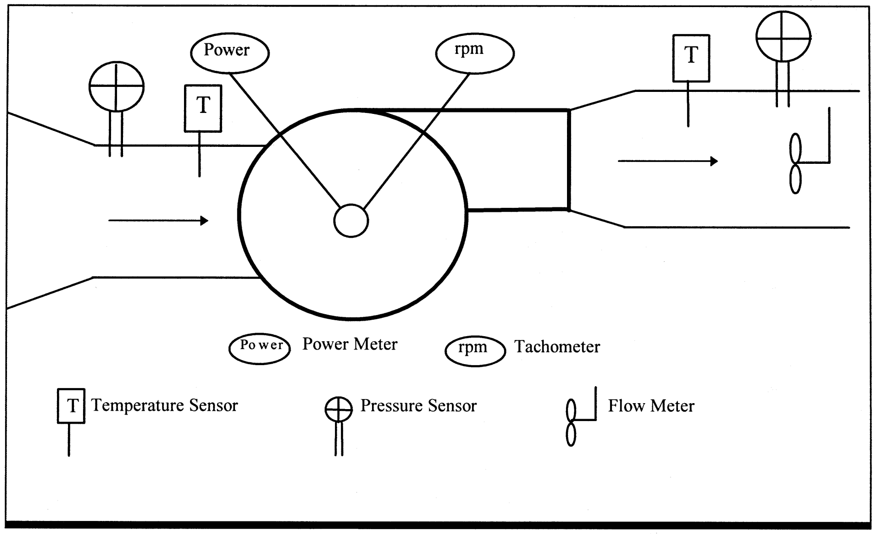

Figure A4-2 Typical centrifugal fan with minimum required instrumentation.

Calculations can also be checked by a heat balance performed on the entire system. These calculations and measurement techniques are detailed in the following standards.

ARI Standard 550-92, Centrifugal and Rotary Screw Water-Chilling Packages. ARI Standard 550 establishes definitions and nomenclature for centrifugal and rotary screw chillers. It also defines the standard full- and part-load rating conditions for these types of chillers so that published ratings will have a consistent basis. Equations for calculation of allowable deviation tolerances from rated conditions are also given for full and part load. ARI Standard 590-92 establishes similar conditions for the rating of chillers utilizing positive displacement compressors.

ARI Standard 590-92, Positive Displacement Compressor Water-Chilling Packages

ASHRAE Standard 30-1978, Methods of Testing Liquid Chilling Packages. ASHRAE Standard 30-1978 prescribes a methodology for testing liquid chilling packages, but it does not specify the test conditions under which the system must operate. Primary and confirming test methods are prescribed, along with test procedures detailing operational limits of the measured parameters, data to be recorded, and calculation of results. Instruments and measurement techniques are referred to other existing standards. The methodology of using primary and secondary confirming test methods should be investigated for applications to field testing of chillers.

In addition to the above-mentioned standards, there are few engineering articles in the literature specifically oriented toward the field testing of chillers. Chiller efficiency and amount of refrigeration produced can be calculated in real time using an energy management control system (EMCS) as shown in Spielvolgel (1982). These calculations require measurements of flow rate and temperature difference that can be recorded and used to calculate the thermal energy flows by the EMCS. Anderson and Dieckert (1990) discuss a method of testing chillers that could be accomplished without machine interruption. A graph of heat rate error as a function of mass flow rate error and temperature differential points to the importance of sensor accuracy for heat rate evaluations. The authors used integrated circuit temperature sensors and dual-rotor insertion flow meters. Because field tests could not be done at "rated conditions," data were compared to the expected values as determined from manufacturer's specifications.

For chiller testing, relative temperature measurement precision is more important than true accuracy because chiller capacity is related to the temperature difference. Relatively simple testing can be used to determine if a chiller has a clean condenser and is performing satisfactorily by comparing a single test against manufacturer's published performance curves (Harmon 1984). A study of rooftop DX cooling equipment monitored energy flows on two units for a three-week period. The results are of interest here for the manner of displaying the results: frequency distributions of kW/ton and scatter plots of kW/ton vs. cooling load. The degradation of performance with part load appeared to vary as an exponential function of the load on the evaporator (Silver et al. 1990).

A San Diego utility monitored chillers for one year at 21 sites from October 1991 to September 1992. Power and Btu flows were measured hourly. Results indicate that, in general, the chillers were operating as expected from manufacturer's and design data. The range of average annual kW/ton efficiencies was 0.74 to 1.09. Six sites operated the chillers adequately. Eleven sites operated multiple chillers at below 50% load, indicating problems in the control logic of chiller staging, and seven sites operated chillers at low loads for long periods of time, indicating oversizing (San Diego Gas & Electric 1993).

A4.2 Equipment Testing Standards: Fans

The theoretical aspects of calculating fan performance are well understood and documented. Fan capacity and efficiency are calculated from measurements of static pressure, velocity pressure, flow rate, fan speed, and power input (Figure A4-2). The difficulties involved in standardizing in-situ performance measurement are the wide variety of fan installations and system configurations. Measurement techniques and calculations are detailed in the following standards.

ANSI/ASHRAE 51-1985, ANSI/AMCA 210-85, Laboratory Methods of Testing Fans for Rating. This standard establishes uniform methods for laboratory testing of fans to determine performance in terms of flow rate, pressure, power, air density, speed of rotation, and efficiency. The units of measurement, definitions, instruments and methods of measurement, and calculations all have some validity for field testing. However, the laboratory equipment setups in this standard are generally precluded for field use because the prescribed duct configurations would require extensive alterations to installed systems.

AMCA Standard 803-87, Site Performance Test Standard for Power Plant and Industrial Fans. This standard establishes uniform methods for measuring the performance of large power plant or industrial fans under actual operating conditions on the site. The standard applies only to fans where the system effect is insignificant. This is determined by the calculation of minimum allowable deviations in the flow velocity profiles and duct geometry. If the installation does not meet the requirements of this standard, AMCA Publication 203-90, *Field Performance Measurement of Fan Systems*, should be consulted to deal with the system effects.

AMCA Publication 203-90, Field Performance Measurement of Fan Systems and AMCA Publication 201-90, *Fans and Systems*. These two standards together provide guidelines for the measurement of fan systems in the field. The major difficulty of field testing fan systems is the difficulty of finding appropriate locations for the required measurements. The major restriction in the choice of traverse planes is the uniformity of the velocity profile. Because of the variety of fans and installations, they are necessarily somewhat general. However, AMCA Publication 203-90, Appendix A, gives 23 examples to illustrate field tests in a variety of fan-system combinations. It describes guidelines for instruments, measurements, and calculations for fan flow rate, static pressure, power input, speed, and air densities.

ASME PTC 11: Fans. ASME Performance Test Code 11 provides standard procedures for testing fans under actual operating conditions. Two approaches are included, one using mass flow rate and fan-specific energy and the other (more common in HVAC applications) using volume flow rate and pressure. The methods in PTC 11 are based on measurements sufficiently close to the fan boundaries that correction for losses between traverse planes and fan boundaries is not required. The code specifies the velocity traverse method as the primary method for flow measurements and simple arithmetic summing to calculate the average flow. Traverse plane limitations are similar to AMCA Publication 203. To account for varied velocity distributions, this code specifies a relatively large number of traverse points and requires the use of directional velocity probes. This method determines a single operating point for the fan in question. Separate tests are required for multiple operating points.

In addition to the above-mentioned standard measurement procedures, there are several articles that have been published in *ASHRAE Transactions* (Stevenson 1976; Clarke 1976; Myers 1976; Zaleski 1976) describe the basis for what was to become the AMCA Publication 203, *Field Performance Measurement of Fan Systems*. Performance ratios, such as the specific fan power (fan power / design air flow rate), can be used to characterize the possibilities of air systems to deliver low annual energy usage (Jagemar 1994).

For example, measurements and handbook data show that for VSD drives:

$$\text{fan power} = (\text{flow rate})^n$$

where

n = 2.0 - 2.5 for return fans

n = 1.5 - 2.0 for supply fans providing static pressure (Jagemar 1994)

A4.3 Equipment Testing Standards: Pumps

The theoretical aspects of calculating pump performance are well understood and documented. Pump capacity and efficiency are calculated from measurements of pump head, flow rate, and power input (Figure A4-3). These calculations and measurement techniques are detailed in the following standards.

ASME PTC 8.2-1990, Centrifugal Pumps. PTC 8.2 establishes rules for conducting pump tests under specified conditions to determine pump head, pump capacity, power input, efficiency, and net positive suction head requirements. The types of pumps in HVAC applications are a limited subset of the pumps covered in this standard. Two sets of testing procedures are described with differing uncertainty and accuracy requirements. The requirements of a particular project will determine which of the procedures is most appropriate. The standard is organized by guiding principles, instruments and method of measurement, and computation of results. Various configurations for the measurement of pump pressure are given. Capacity measurement is referred to other standards, with the applied limitations of the calibration and accuracies in this standard. For field application, the recommended accuracies should be compared to the requirements of the project in question and the limits of the available measurement techniques.

Hydraulic Institute, *Centrifugal Pump Test Standards*. The Hydraulic Institute test standards apply to centrifugal, vertical turbine, mixed flow, and axial flow pumps and provide limiting conditions for measurement of capacity, head, speed, and input power. The tests are intended for rated and or specified conditions only and do not include provisions for part-load performance. Calculations and examples are included for all performance characteristics and for methods of measuring pressure, capacity, speed, and shaft power.

In addition to the above-mentioned standards, Pellet (1974) gives advice on field performance measurement of pumps, stressing good engineering practice and practical solutions to common problems. Measuring techniques for pump head, capacity, and power are covered. Pump flow can be calculated from a pump curve using a measured pressure differential across the pump. Although the accuracy of this method depends on the shape of the pump curve, this method may still have applications such a check against other flow measurements. Advances in measuring and recording technol-

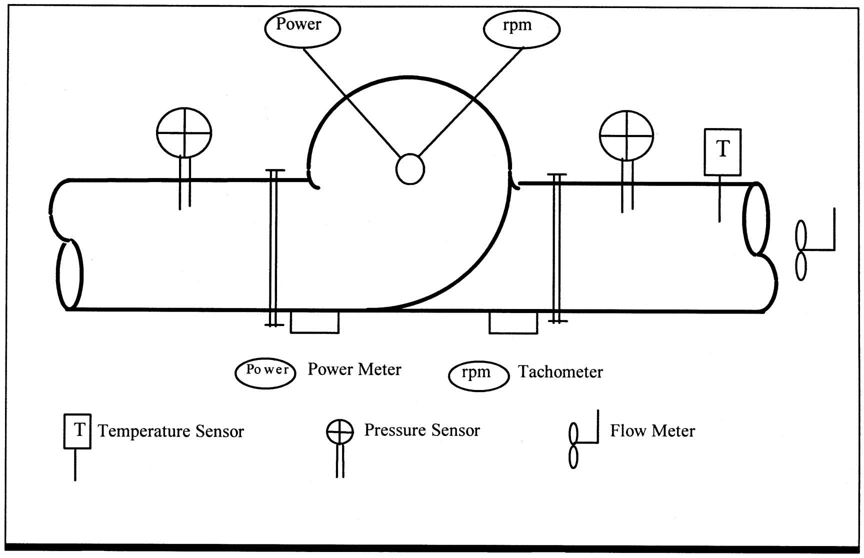

Figure A4-3 Typical centrifugal pump with minimum required instrumentation.

ogy have made many of the technical aspects of this article obsolete, but the recommended practices and troubleshooting techniques are valid. Pump energy conservation in HVAC systems is often oversimplified toward comparisons of pump efficiencies. The type of system and its control strategy are essential for accurate estimation or calculation of annual energy use. A broad range of energy use can occur with various schemes for the same system (Rishel 1983).

A4.4 Equipment Testing Standards: Motors

These standards are include for completeness. In this project, the motors are considered a part of the equipment being tested. In addition, these motor testing standards are not applicable in most in-situ applications because they depend on shaft loading procedures that usually require disconnection of the motor in question.

ANSI/IEEE Standard 112-1992, Standard Test Procedures for Polyphase Induction Machines

ANSI/IEEE Standard 113-1985, Standard Test Procedures for Direct Current Machines

ANSI/IEEE Standard 115-1983, Standard Test Procedures for Synchronous Machines

In addition to the above-mentioned standards for motors, several engineering papers have been published for calculating efficiencies for chillers, fans, and pumps, which requires accurate testing of the driving motors. Hoshide (1994) describes utilizing the nearly linear relationship between motor slip and load for checking motor load. With motor load calculated and input power measured, motor efficiency is easily calculated.

Lobodovsky et al. (1989) describe a utility pilot project for field testing of electric motor efficiencies and determination of economically viable alternatives. The procedure used for field measurements was the IEEE 112 method E/F. Required measurements for this procedure are load and no-load voltages, amperes, power factor (or power), shaft RPM, and stator resistance. Field experience is documented for the testing of 60 industrial motors, noting difficulties especially in the no-load measurements because of the need to uncouple the motor in question.

An Arizona program for replacement of HVAC motors discovered that the slip method of motor testing is prone to large errors because of the effects of incorrect nameplate data, motor temperature, operator error, operating voltage, and motor rewinding effects (Jowett 1994). A simple amperage test can determine motor loading above 50% with reasonable accuracy, while lower motor loading requires more involved tests as documented by Lobodovsky et al.

In recent years, the use of variable speed drives (VSD) to control fans, pumps, compressors, and other equipment has been rising steadily. Their use increases the efficiency of equipment at part load or flow. The fan or pump affinity laws predict that reductions in flow reduce the input power requirements according to a cube function. However, system interactions, such as static pressure, are not accounted for in the affinity laws, and experience has indicated that the actual system curve using VSD equipment will follow a square function, rather than the theoretical cube function (Stebbins 1994). Englander and Norford (1992) propose analysis of VSD applications on the basis of energy use characteristics or system characteristics. Five distinct categories are identified. Simplified general expressions for pump or fan power as a function of flow and pressure offset, for throttled and VSD control, are presented.

A4.5 Equipment Testing Standards: Boilers and Furnaces

There are two principal methods for determining boiler efficiency, the input-output method and the heat loss method, also known as the direct method and the indirect method, respectively. Both are recognized by the American Society of Mechanical Engineers (ASME) and are mathematically equivalent. They would give identical results if all the required heat balance factors were considered and the corresponding boiler measurements could be performed without error. ASME has formed committees from members of the industry and developed the Performance Test Code (PTC) 4.1a, *Steam Generating Units* (ASME 1974), that details the procedures of determining boiler efficiency by the two methods mentioned above. The following discussion has been extracted from Wei (1997).

Boiler efficiency is defined as the percentage of heat input to the boiler that is absorbed by the working fluid. The general practice in the United States is to base boiler efficiency on the higher heating value (HHV) of the fuel, whereas in most countries using the metric system it is customary to use the lower heating value (LHV) of the fuel (Aschner 1977). Practical design considerations limit the boiler efficiency that can be achieved. Typically, boiler efficiencies range from 75% to 95% for utility boilers (Stallard and Jonas 1996). For industrial and commercial boilers, the average efficiency ranges from 76% to 83% on gas, 78% to 89% on oil, and 85% to 88% on coal (Payne 1985).

The input-output method is the easiest way to determine boiler efficiency. It was standard for a long time but is little used now (Gill 1984). In this method, the heat supplied to the boiler and the heat absorbed by the water in the boiler in a given time period are directly measured. Thus, the efficiency of a non-reheat boiler is given by

$$\eta_b = \frac{Q_a}{Q_i} \times 100 , \quad \text{(A4.5-1)}$$

where

Q_a	=	heat absorbed, Btu/h,
	=	$\sum m_o h_o - \sum m_i h_i$,
$m_o h_o$	=	mass flow-enthalpy products of working fluid streams leaving boiler envelope, including main steam, blowdown, soot blowing steam, etc.,
$m_i h_i$	=	mass flow-enthalpy products of working fluid streams entering boiler envelope, including feedwater, desuperheating sprays, etc.,
Q_i	=	heat inputs, Btu/h,
	=	$V_{fuel} \times HHV + Q_c$,
V_{fuel}	=	volumetric flow of fuel into boiler, SCF/h,
HHV	=	fuel higher heating value, Btu/SCF, and
Q_c	=	heat credits, Btu/h.

Heat credits are defined as the heat added to the envelope of the steam-generating unit other than the chemical heat in the fuel “as fired.” These credits include quantities such as sensible heat in the fuel, the entering air, and the atomizing steam. Other credits include heat from power conversion in the pulverizer or crusher, circulating pump, primary air fan, and recirculating gas fan.

For an abbreviated test (ASME 1974), heat credits can be ignored and the efficiency can be evaluated by using the results of only seven measurements (fuel flow rate, steam flow rate, steam and feedwater pressure and temperature, and HHV of the fuel). The trouble with this method is that the accuracy of these measurements, especially the flow rates, is sometimes an issue. To ensure that accurate readings are obtained, the measuring device should be inspected and the transducers calibrated. However, in normal practice, often only the transducer is taken out for calibration and the measuring device is left untouched since its inspection requires the tear-down of some equipment or a major plant outage. This is exactly what happened in the case study of a university’s central utilities plant. Haberl et al. (1993) pointed out this problem and noted that it must be resolved to implement an operational optimization program. However, it was not discussed in a previous boiler testing program (Dukelow 1991) in this plant. As a consequence, even though a meter is newly “calibrated,” the readings it provides may not be accurate. Methods that can identify inaccurate meters without interrupting the plant’s normal operation are needed.

Aside from the drawback mentioned, the direct method is also limited in that it only gives the efficiency of the boiler but does not indicate where the losses occur and the way to minimize them. Generally, the best method for efficiency determination is the heat loss method. Boiler efficiency equals 100% minus the losses. The heat loss method concentrates on determining the heat lost from the boiler envelope or the heat not absorbed by the working fluid. The heat loss method determines boiler efficiency as

$$\eta_b = \frac{Q_a}{Q_i} \times 100 \quad \text{(A4.5-2)}$$

$$= \frac{Q_i - Q_{loss}}{Q_i} \times 100$$
$$= 100 - L_{df} - L_{fh} - L_{am} - L_{rad} - L_{conv} - L_{bd} - L_{inc} - L_{unacct} \quad \text{(A4.5-3)}$$

where

Q_{loss}	=	heat losses, Btu/h;
L_{df}	=	dry flue gas heat loss,%;
L_{fh}	=	fuel hydrogen heat loss,%;
L_{am}	=	combustion air moisture heat loss,%;
L_{rad}	=	radiative heat loss,%;
L_{conv}	=	convective heat loss,%;
L_{inc}	=	encompassed fuel loss,%;
L_{bd}	=	blowdown heat loss,%;
L_{unacct}	=	unaccounted for heat losses,%.

The heat losses include the flue gas loss (sensible and latent heat), radiation and convection loss, fuel loss due to incomplete combustion, blowdown loss, and losses that are unaccounted for. The flue gas loss is the major loss and is generally determined by a flue gas analysis; it varies with flue gas exit temperature, fuel composition, and type of firing (Aschner 1977). The radiative and convective loss can be taken from the standard American Boiler Manufacturers’ Association (ABMA) curve (Babcock and Wilcox 1992).

For a boiler fired with solid fuel, an unaccounted loss of 1.5% is commonly used; for a gaseous or liquid fuel boiler, the commonly used value is 1% (Dukelow 1991). Blowdown is sometimes considered a loss (Witte et al. 1988; Aschner 1977). Although it is not a useful heat output, it is not considered a loss in the ASME Performance Test Code because the boiler has properly transferred the heat from the fuel to water. The dependence of these losses on boiler load is an important boiler characteristic and is the major factor considered in boiler load management (Payne 1985; Peters 1992; Shane 1981; Yaverbaum 1979).

In the procedures used to calculate the heat losses, the two accepted methods are the "weight" method and the "mole" method. The "weight" method is used in the heat loss method of the ASME Performance Test Code, in which a combined standard mean specific heat of 0.24 Btu/lb-°F is used for the dry flue gas. With the "mole" method, the combustion chemistry formulas are used to determine the number of moles of each flue gas constituent, and the individual specific heat of that constituent is also used. For this reason, the "mole" method is slightly more precise than the standard ASME method.

Accuracy or uncertainty in boiler efficiency calculations is a function of the quantities measured and the method employed to determine the efficiency. Using the input-output method, these quantities are related to overall efficiency. For example, if the measured boiler efficiency is 80%, then an error of 1% in one of the quantities measured will result in a 0.8% error in the efficiency. However, for the heat loss method, the measured and determined parameters are related to net losses. Therefore, for the same boiler of 80% efficiency, a measurement error of 1% in any quantity would affect the overall efficiency by only 0.2% at most (1% of the measured losses of 20%). As a result, the heat loss method is inherently more accurate than the input-output method for boilers with efficiencies above 50%.

Combustion efficiency is often encountered in the literature when describing boiler performance. The combustion efficiency is a measure of the fraction of fuel-air energy that becomes available during the combustion process (Thumann 1988). It is given by

$$\eta_c = \frac{|h_p| - |h_f + h_a|}{Q_i} \times 100 \qquad \text{(A4.5-4)}$$

where

η_c = combustion efficiency,%;

h_p = enthalpy of products, Btu/lb;

h_f = enthalpy of fuel, Btu/lb;

h_a = enthalpy of combustion air, Btu/lb.

If the products of combustion were cooled to the temperature of the entering fuel and combustion air before leaving the boiler, a 100% combustion efficiency can be achieved. However, this is impractical since it would require infinite heat transfer surface and would cause corrosion at the boiler cold ends due to moisture condensation. Generally, flue gas leaves the boiler at an elevated temperature, causing the combustion efficiency to drop. Fuels of higher hydrogen content produce combustion gases that have high specific heats; thus, the flue gas loss tends to be greater and the combustion efficiency is lower. The relationship between boiler efficiency and combustion efficiency can be expressed by the following equation (Garcia-Borras 1983):

$$\eta_b = \eta_c - L_{rad} - L_{conv} - L_{unacct} \qquad \text{(A4.5-5)}$$

Generally, the loss terms on the right-hand side of the above equation are small for a well-insulated boiler. Therefore, the combustion efficiency is approximately equal to the boiler efficiency. This equality is NOT valid, however, for boilers with poor insulation, poor blowdown control, or both of these faults.

There are also empirical, well-proven methods for estimating the stack loss (L_{df}, L_{fh}, and L_{am}) (Aschner 1977), radiation loss (L_{rad}), and convection loss (L_{conv}) and losses unaccounted for (L_{unacct}) (Fryling 1966); there is also statistical data for the other losses (Aschner 1977; Payne 1985). Combustion efficiencies for different types of fuels under various combustion conditions are available in tabular forms (Dyer and Maples 1981; Taplin 1991; Dukelow 1991). Their application and comparison with test results are used to investigate the influence of boiler design and operation on efficiency and fuel use.

The methods mentioned above can be readily applied to heat recovery steam generators (HRSGs), provided that heat content in the entering gas stream can be determined and the rate of supplementary firing, if there is any, is known. Instructions for testing an HRSG are also described in the ASME Performance Test Code.

In-Situ Boiler Performance Evaluation

In-situ boiler performance monitoring and evaluation is important to the overall efficiency of a power plant, which directly impacts operating cost. Boilers and their auxiliaries also account for the largest loss of thermodynamic availability in power plants (Gorzelnik 1985).

Various techniques are available for in-situ boiler performance evaluation. Chernick (1985) described three approaches for determining how well in-situ electric power generating units perform and discussed the advantages and applications of each. These approaches are the (a) self-referent method, (b) the comparative method, and (c) the absolute method. Other methods include the (d) entropy method and (e) the exergy method.

In the first method, the self-referent method, each unit's performance can be determined by a self-referent standard based on the unit's past performance. This self-referent method is easy to apply, but it does not usually produce fair and even-handed standards. It is inherently stricter for those units with good performance histories than for those with poor past performance.

In the second method, the comparative method, standards are based on comparative analyses, which aggregate the experience of other units. However, it is difficult to justify direct comparisons between units due to vintage, age, operating pressure, size, fuel type, and so on.

In the third approach, the absolute method, standards are to be based on absolute measures of proper performance. They do not depend on actual performance data. The unit's performance is compared with its design performance.

Traditionally, the performance of a boiler is evaluated by its efficiency, which is based on the first law of thermodynamics. This approach is essentially an energy balance between the various inputs, outputs, and losses. It can be applied to determine the thermal efficiency of individual components as well as the overall plant. The drawbacks are that it does not indicate whether an energy conversion process is possible, the direction of the process, or the conditions under which it may occur. Despite its limitations, this method is widely accepted for its simplicity and ease of use.

Two other approaches for boiler performance evaluation that are based on the first and second laws of thermodynamics have gained academic popularity recently. They are the entropy method and the exergy method. The entropy method calculates the availability losses, and the exergy method calculates the thermodynamic availability. They are both essentially an exergy balance and reveal the losses due to irreversibility during the energy conversion process. Niu (1992) employed a second law analysis in his boiler model to simulate and analyze a power system. The model can be applied to different power systems with different configurations The analyses included the combustion heat flux, gas temperature distribution, feedwater heater and boiler unit performance, and major operational parameters' effects.

Al-Bagawi (1995) carried out a full energy and exergy analysis to identify the potential for improving power plant performance. The exergy analysis showed a detailed breakdown of exergy losses of the different components in the plant. Liu (1994) investigated the exergy destruction in a conventional steam power plant. Efficiencies based on the first law and second law of thermodynamics were calculated for a number of components and for the plant. The results showed that high first law efficiency did not necessarily mean high second law efficiency.

Although second law analysis offers greater insights into the performance of a thermal system, the problem is how to develop a practical means of applying the second law. Lang and Horn (1990) presented the fuel use index (FCI) for this purpose. The FCI indicates why and where in the system fuel is being consumed. It points out the contribution of each individual component to the electricity production or to thermodynamic losses in terms of fuel use. However, this approach requires accurate measurements of plant variables.

Ganapathy (1990) illustrated a simplified approach to predict the overall performance of HRSGs. Based on known or assumed pinch (the temperature difference between the flue gas and water as the flue gas cools to the point at which water starts to evaporate) and approach (the difference between the temperature of feedwater exiting the economizer and the temperature at which water starts to evaporate) points, a "design" is simulated, the gas/steam temperature profiles are determined, and the steam flow is obtained. The procedure may be used for both fired and unfired HRSGs. Kuppuraj (1986) presented a nomogram that can quickly estimate the performance of HRSGs under off-design conditions. Collins (1991), on the other hand, described a computer program that could execute off-design condition performance analyses of HRSGs. The HRSG is simply treated as a heat-transfer surface. Dechamps (1995) described a numerical method used to compute the transient performance of HRSGs.

Current technology makes it possible to perform calculations and equipment diagnosis in near real-time (Harmon et al. 1992). On-line performance monitoring systems provide plant operators, engineers, and management with real-time operating data. Continuous display of data enables the operator to alter the operating conditions and instantly view the benefit or consequence of his/her action.

Boiler performance monitoring by itself provides little but an accumulation of numbers. It is only when this mass of raw data is validated and presented to the operator in a form suitable for his/her guidance that it gains meaning. However, data from one or more sensors may be inaccurate. Such problems become acute when using historical data to evaluate a boiler's performance and determine its characteristic curve. Hence, data validation is essential for any performance evaluation.

Although accurate data can be obtained by installing state-of-the-art instruments, budget constraints often prohibit the adoption of this practice. To remedy this problem, a broadly useful diagnostic methodology was developed by Wei (1997) to determine the in-situ operating characteristics of power plant boilers when metered data is either missing or obviously erroneous. Wei's methodology is able to analyze conflicting measurements and utilize analytic redundancy (AR) to deduce the measurement or measurements, which are substantially in error without shutting down the plant and recalibrating all instrumentation. His work showed, through the case study power plant, that the methodology is quite robust in identifying faulty instruments in plants, which possess a low degree of hardware redundancy. Once the malfunctioning meters are identified and the historical data are corrected, boiler characteristic curves were generated to guide the daily operation and assist future implementation of on-line optimal load allocation.

A4.6 Equipment Testing Standards: Thermal Storage

ASHRAE has developed *Standard 150-2000, Method of Testing the Performance of Cool Storage Systems*. This standard was developed to provide a uniform method for evaluating the performance of cool storage systems installed in buildings or central plants, and it is intended to be used by owners, operators, consultants, and others. The standard provides a method to determine the cooling performance of a given installation at the time of turnover to the owner or at any time during its useful life. It includes options for testing a system at times when less than the peak load is available and includes a method for defining test loads that enable the user to determine if the cool storage system would perform as expected when subjected to the actual peak load. The standard can also be used to determine the maximum performance of a new or existing system.

In order to utilize the standard, the user is required to provide certain information about the system necessary to define the test conditions and requirements, including the following:

- The load profile against which the storage device or system must be tested. The user should note that the usable storage capacity of a given storage device or system will vary depending on the load profile.
- The tests that are to be performed. Users may elect to perform any number of the individual tests defined in the standard.
- System parameters such as maximum usable discharge temperature, maximum usable cooling supply tempera-

ture, and criteria for determining the fully charged and fully discharged conditions.

- For the systems capacity tests, the boundaries of the system or portion of the system that is to be tested.

A4.7 Equipment Testing Standards: HVAC System (Air Side)

ANSI/ASHRAE 111-1988, Practices for Measurement, Testing, Adjusting, and Balancing of Building Heating, Ventilation, Air-Conditioning, and Refrigeration Systems. ASHRAE Standard 111 provides uniform procedures for measuring and reporting the performance of HVAC&R equipment in the field. It includes methods of air and hydronic measurements for flow, temperature, and pressure and makes recommendations for evaluating the validity of collected data considering system effects. Some system characteristics can be measured directly while others must be calculated from measured data. Equations for these calculations are included in this standard. Procedures are outlined for calculating flow rates using installed system balancing devices and using system components for which a rated Cv (valve constant) is known. Accuracy requirements are given, but the standard does not provide detailed procedures for calibration of measuring techniques or assessment of measured data.

A4.8 References

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A5 Cost and Error Considerations

The material for A5, Cost and Error Considerations, was graciously provided by the California DSM Measurement Advisory Committee (CADMAC). It originates from "Measurement Methods Guidebook," "Development of Statewide Metering/Monitoring Protocols," May 1994, prepared by SBW Consulting, Inc., and NCAT-Development Corporation under the guidance of CADMAC's DSM Monitoring Standard subcommittee. It has been edited as necessary to fit within the framework of ASHRAE Guideline 14. (The preceding notation has been requested by CADMAC in order to use the following information.)

A5.1 Introduction

A5 provides an analysis of the cost and error considerations of alternative methods that can be used to implement the physical measurements referenced in this guideline. Clause A5.2 classifies measurement methods used in this analysis. A5.3 defines how to interpret the information provided on the cost of site-specific classes. A5.4 specifies which costs are excluded from the analysis. A5.5 discusses the impact of sampling on measurement cost and error. A5.6 describes each of the alternative classes and provides data on the cost and error associated with each class. A5.7 provides definitions of the sensor types that are referenced in A5.6. It should be noted that these definitions are included to provide context for this analysis and may not be applicable elsewhere in this guideline.

A5.2 Measurement Classes

For each type of measurement, cost and error information has been provided in Clause A5 on the following four classes of measurement methods:

Class 1. This class of methods relies on physical measurements this can be implemented during the course of a site inspection or audit. For example, in a lighting power measurement, the spot measurement method requires a portable power meter and generic information on operating hours. The portable meter provides instantaneous measurement of true power for each type of lighting fixture. This information, along with a count of the fixtures by type, and generic lighting operating hours for each type of site, can be combined to produce a measurement of lighting power usage. As only instantaneous metering is required at each site, there is no need for data recording equipment; thus, the cost of data acquisition for this method is assumed to be small.

Class 2. This class of methods relies on physical measurements that are repeated at regular intervals, e.g., 30 minutes or 1 hour, over a period that is longer than the duration of a site visit but is short enough that measurement equipment can be shared among a number of sites in an evaluation. The measurement period must be long enough to provide information about the typical hours of operation or utilization of the affected energy systems. Continuing the lighting power example, the site-specific measurements would provide information on true power use of the lights during the measurement period. These data are scaled to an annual basis to complete the measurement of power. These methods require some form of data recording equipment at each site, but the cost of this equipment is shared among a number of sites.

Class 3. This class of methods relies on physical measurements that are repeated at regular intervals over a period that is longer than the duration of a site visit and less than a month. The measurement period must be long enough to provide information about the typical hours of operation or utilization of the affected energy systems. These methods are identical to the previous short-term method, except that data equipment costs are not shared with other sites in the study. These methods will be required in certain circumstances where the overall schedule for evaluation does not allow for long-term measurements or there is no long-term variation in the systems that are monitored.

Class 4. This class of methods relies on physical measurements that are repeated at regular intervals over a period that is longer than one month. The measurement period may extend across seasons, or potentially across years, as may be necessary to provide information on the operating characteristics of the affected systems. These methods have the lowest measurement error, as variations in operating hours or utilization are directly recorded. However, these methods have the highest cost, as data recording equipment must be devoted to each site for the longest measurement period, and there is a large quantity of data to be verified, managed, and analyzed.

A number of specific methods are described for each class. These specific methods involve the use of different types of sensors, such as the sensors that are available for measuring relative humidity. Specific methods may also be defined by the type of data recording equipment used, e.g., battery-operated single-channel data loggers vs. multi-channel data recorders that require external power. Costs and error are affected by the type of sensor and data recorders that are selected.

A5.3 Measurement Cost. Figure A5.1 is a sample page from the A5.6.1 Table of Site Specific Measurement Methods. This table lists a large number of methods that can be used to obtain the physical measurements, e.g., electric use, which might be included in a monitoring project. The table provides a description of each alternative measurement method, including the class of method (see Annex A5.2 for definitions of method classes), type of application, sensor type, and the data acquisition system (DAS) type. A range of costs is provided for each method listed in the table.

Many sensor and data acquisition system installation costs are dependent upon the specific conditions found in a customer's buildings or facilities. The cost analyses presented here assume average or "typical" site specific circumstances for data acquisition system installation and assume that all sensors are in close proximity to the data acquisition system. In reality, circumstances could be much different and installation costs much higher. For example, the "typical" installation of a telephone line may result in essentially no project costs if a telephone jack is present at the data acquisition system location and the customer is willing to share the telephone. Alternatively, if a new telephone line is required, there are the costs of activating telephone service as well as the costs of bringing a telephone line to the data logger. At some sites, an instrument technician may spend a day or more coordinating and installing a telephone line to a data logger.

The installation of signal cable provides another example of how costs encountered in the installation of energy monitoring equipment can vary across sites. For the cost estimates provided in this guideline, it has been assumed that sensors are in close proximity to the data acquisition system (DAS). However, this will not always be the case. Sensors are often located a considerable distance from the DAS. For example, electrical end-use monitoring designs frequently call for measurements at the device or appliance level. While the specified devices may be served from the same electrical panel, it is just as likely that they are not. In fact they may be separated by several floors as well as several hundred feet. In these circumstances, cable costs, including installation, may far exceed sensor costs.

Conforming to existing building standards can also dramatically increase monitoring equipment installation costs. Installing sensors in finished space often involves concealing wire either with surface-mounted wire molding or by "fishing" wire through building cavities. Either route is expensive. Many commercial buildings route all wire in conduit, even though conduit may not be specifically required for signal cable under most electrical codes. In that case routing signal cable from a single sensor back to the data logger might add hundreds of dollars to the cost of that sensor's installation.

A5.6.1 The Table of Site Specific Methods provides a range of costs for sensor and data acquisition system installation. The low value in this range would occur under the best possible site conditions. In difficult situations, actual sensor or data logger installation costs could be much higher. They may in fact be higher than the high values provided in the table, which represents the costs of a typical site, but not the worst case.

The table contains a number of coded values, e.g., DAS types, abbreviations, and computed columns, which must be thoroughly understood before the table can be reliably applied to the design of a monitoring project. Presented below are complete definitions for each column of the table.

Column 1: Class of Method/Application/Sensor Type. This column defines the specific measurement method. There are three components to the definition of a method. The first component of the definition is the class of method. A complete

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized Cost per Measurement Point ($)	
Class of Method / Application / Sensor Type (1)	DAS Type (2)	Tech. Note (3)	Purchase (4) Low (4.a)	Purchase (4) High (4.b)	Install & Remove (5) Low (5.a)	Install & Remove (5) High (5.b)	Maintenance (6) Low (6.a)	Maintenance (6) High (6.b)	Purchase (7) Low (7.a)	Purchase (7) High (7.b)	Install & Remove (8)	Maintenance (9) Low (9.a)	Maintenance (9) High (9.b)	Low (10)	High (11)
Measurement Type: Electric Consumption															
Spot Measurement															
Whole Building or Service															
Existing Energy Meter	1	1	0	0	28	28	0	0	0	0	0	0	0	28	28
Existing Demand Meter	1	2	0	0	28	28	0	0	0	0	0	0	0	28	28
Component, Device, or Appliance															
Portable Watt Meter	1	3	440	11,000	28	28	0	2	0	0	0	0	0	32	139
Demand Meter	1	4	500	1,000	0	0	0	0	0	0	0	0	0	5	10
Short-Term, Shared Equipment															
Whole Building or Service															
IR Pulse Detector	2	5	83	83	110	110	2	2	880	2,200	440	8	12	306	392
	3	5	83	83	110	110	2	2	1,650	4,400	660	8	14	306	435
	4	5	83	83	110	110	2	2	2,950	3,600	880	6	8	248	306
Whole Bldg or Service - Existing CTs															
Shunted CTs on Secondaries	4	6	275	330	55	55	2	2	2,950	3,600	880	36	69	876	1,583
Whole Bldg or Service - New Meter															
Shunted CTs	4	7	275	660	220	220	4	5	2,950	3,600	880	36	69	1,043	1,834
Component, Device, or Appliance															
Portable Recording Watt Meter	5	8	7,700	11,000	55	55	25	35	0	0	0	0	0	2,005	2,840
Portable Cumulative Run-Time Meter	5	9	150	250	55	55	1	1	0	0	0	0	0	94	119
Portable Time-of-Use Run-Time Meter	5	10	450	600	55	55	2	3	0	0	0	0	0	170	208
Shunted CTs	4	11	250	660	220	220	4	5	2,950	3,600	880	25	69	806	1,834

Figure A5-1 Sample page from the Table of Site Specific Measurement.

definition of the four possible classes of methods can be found in A5.2. Briefly these classes are defined as follows:

1. *Class 1.* This method relies on physical measurements that can be implemented during the course of a site inspection or audit.
2. *Class 2 (Shared Equipment).* This method relies on physical measurements that are repeated at regular intervals, e.g., 30 minutes or 1 hour, over a period that is longer than the duration of a site visit but is short enough that measurement equipment can be shared among a number of sites in an evaluation.
3. *Class 3 (Devoted Equipment).* This method relies on physical measurements that are repeated at regular intervals over a period that is longer than the duration of a site visit and less than a month. The measurement period must be long enough to provide information about the typical hours of operation or utilization of the affected energy systems. This method is identical to the previous short-term method, except that costs of sensors and data acquisition equipment are not shared with other sites in the study.
4. *Class 4 (Devoted Equipment).* This method relies on physical measurements that are repeated at regular intervals over a period that is longer than one month. The measurement period may extend across seasons, or potentially across years, as may be necessary to provide information on the operating characteristics of the affected systems.

The class of measurement method selected for a monitoring project will affect the project's measurement costs and likely measurement error. Some of the component costs that are displayed in the Table of Site Specific Measurement Methods are affected by the class that is selected. Classes 1 and 2 allow the costs of the measurement equipment to be amortized over a number of monitoring sites. An amortization multiplier has been assigned to each class of methods to assign the correct portion of the costs to a measurement point at a specific measurement site. The table below lists the amortization multipliers that have been used in this analysis.

TABLE A5-1
Amortization Multipliers for Four Classes of Measurement Methods

Class of Method	Amortization Multiplier
1	.01
2	25
3	1.00
4	1.00

As the table shows, we have assumed a multiplier of.01 for Class 1 methods. This implies that the equipment for Class 1 methods, e.g., an amp probe, can be used at least 100 times.

The second component of the method definition describes the type of application where it is technically feasible to use a specific measurement method. The sample page shown in Figure A5.1 shows a number of possible applications of electric use measurement methods, including whole building or service and building component, device, or appliance. The first of these applications refers to the circumstance where the monitoring objective is to measure electric use of an entire building or use at the point where electric service is supplied to a facility. The second example applications refers to the measurement of electric use for specific end-use loads found at a customer site. These end uses may be a component of the customer's energy systems, such as the HVAC system, or it may be a particular type of device or appliance such as personal computers.

The last part of the method definition describes the device to be used in sensing the physical quantity that is measured. For example, an IR pulse detector is a device that attaches to an electromechanical kilowatt-hour meter, detects the rotation of the meter, and produces a series of pulse outputs. The number of pulses per second is proportional to the rate of electric power use. Definitions for each type of sensor referenced in the Table of Site Specific Measurement Methods are provided in A5.7.

Column 2: DAS Type. This column contains a code (1, 2, 3, 4, or 5), which indicates the type of data acquisition system (DAS) required by each method. Data acquisition systems are equipment associated with software and firmware used to capture and store the output of sensors and make that data available in appropriate engineering units. Data acquisition systems include all types of data recorders and loggers and their associated software or hardware used for data retrieval and conversion to engineering units. Devoted data logging devices that must be manually read, such as battery operated lighting loggers, are also data acquisition systems. Five DAS types are referred to in the site specific measurement methods tables. Definitions for these five types are as follows:

1. *Manual Reading.* Some sensors display their output in a human readable form although they do not have a data storage capability. These sensors can be manually read and the reading entered directly into the database used to store monitoring results.

2. *Four-Channel Digital/Pulse Recorders.* This type of DAS is only capable of recording information from sensors that produce digital or pulse output. A four-channel configuration has been assumed for the purposes of this guideline, although other configurations are available.

3. *Eight-Channel Analog to Digital Converter and Digital/Pulse Recorders.* This type of DAS is capable of recording information from sensors that produce analog, digital, or pulse output. An eight-channel configuration has been assumed for the purposes of this guideline, although other configurations are available.

4. *Sixteen-Channel Analog to Digital Converter and Digital/Pulse Recorders with On-Board Watt-Hour Metering*. This type of DAS has the same capabilities as type 3, plus the electronics required to convert current and voltage inputs to an output that is proportional to the rate of electric power use. A 16-channel configuration has been assumed for the purposes of this guideline, although other configurations are available.

5. *Dedicated Data Logger.* This type of DAS is integrated with specific types of sensors. Examples include battery-operated temperature sensors and lighting loggers. Sensors are attached to a unit that converts the sensor output to engineering units and stores these values. Often this type of DAS has a built-in data display. Certain makes are capable of storing multiple data values for various time periods or operating conditions. Some form of connection to a personal computer is required to retrieve the stored data values for analysis.

Column (3)—Technical Note (Tech. Note). This column contains a reference to a technical note that provides further information about the application and cost of a measurement method.

Columns 4 through 9. These columns provide the input data used to compute the cost per measurement point for each measurement method. The definitions for each cost component are provided below. Some of these cost components contain estimates of labor costs. These estimates are based on $55 per hour labor rate. The number of hours, by labor category, associated with any cost component will be described in the referenced technical note (A5.6.2).

Columns (4a and 4b)—Sensor Purchase Cost. Columns 4a and 4b contain the price of the sensor and miscellaneous materials such as wire and junction boxes. Also included are any specialty contracting costs, such as for hot taps, that are associated with a particular sensor. Sensors vary in cost and accuracy across make and model. Column 5a contains the lowest value in the price range and Column 5b the highest. A 10% procurement and handling markup is included in these price estimates.

Column (5a and 5b)—Sensor Install and Remove Cost. Column 5a contains the lowest value in the price range and column 5b the highest. Columns 5a and 5b contain the labor and material costs associated with sensor installation and removal. Sensor installation and removal costs are assumed to be identical. The referenced technical note describes the number (or range) of labor hours by labor category required for installation and removal.

Columns (6a and 6b)—Sensor Maintenance Cost. Columns 6a and 6b contain the labor and material cost for maintaining the sensor during the assumed measurement period. The assumed measurement period for each of the four classes of measurement methods is shown in the table below.

TABLE A5-2
Measurement Periods for Four Classes of Measurement Methods

Class of Method	Measurement Period
1	1 Day
2	1 Month
3	1 Month
4	1 Year

Considering these measurement periods and the likely rate of equipment failure, an annual sensor maintenance cost multiplier was developed for each measurement method. The maintenance cost for class 4 methods has been used as a baseline for determining the value of the multiplier. Sensors remain at a site for one year for class 4 methods. Normal maintenance costs for this class are assumed to be 0.05 times the sum of the sensor purchase price and the installation and removal cost. High maintenance costs for this class would be computed with a multiplier of 0.10. Some sensors have unique maintenance requirements, such as chilled mirror dew-point sensors. Unique maintenance multipliers have been developed for these sensors. The maintenance multiplier used for any specific sensor is described in the referenced technical note.

Columns (7a and 7b)—DAS Purchase Cost. Columns 7a and 7b contain the price of the DAS and the associated wire and miscellaneous parts required for each measurement method. Data acquisition systems vary in cost and accuracy across make and model. Column 7a contains the lowest value in the price range and Column 7b the highest. A 10% procurement and handling markup is included in these price estimates. Only a portion of the DAS cost is assigned to each measurement point in computing the total amortized costs shown in Columns 10 and 11. The fraction of the DAS costs assigned to each channel is determined by the channel capacity (4, 8, or 16), the fraction of that capacity that is typically filled with active channels, and the amortization multiplier, as described for Column 1.

Column (8)—DAS Installation and Removal Cost. This column contains the labor and material costs associated with the installation and removal of the DAS. It has been assumed that the removal cost is 0, as the removal costs are very small compared to the installation costs, which include the labor require to perform on-site verification of the measurement system operation for each measurement point. However, in some circumstances, particularly when DAS components must be installed in finished spaces, there may be significant removal costs.

Columns (9a and 9b)—DAS Maintenance Cost. Columns 9a and 9b contain the labor and material cost for maintaining the DAS during the assumed measurement period. The assumed measurement period for each of the four classes of measurement methods is shown in Table A5-2. Considering these measurement periods and the likely rate of equipment failure, an annual DAS maintenance cost multiplier was developed. The multiplier is zero for DAS types 1 and 5 (see definitions of DAS types in the discussion for Column 2). The multiplier is zero for DAS types 1 and 5 because their maintenance cost is reflected in the sensor maintenance cost in Columns 6a and 6b. The multiplier is 0.05 for DAS types 2, 3, and 4. The DAS maintenance cost is equal to the maintenance multiplier times the sum of the DAS purchase price and the installation and removal cost.

Columns 10 and 11—Total Amortized Cost per Measurement Point. These columns contain the total amortized cost per measurement point, which is sum of the amortized cost of the sensor plus the portion of the amortized DAS cost that is assigned to each active DAS channel. The amortized sensor cost is computed as follows:

Amortized Sensor Cost
= (Sensor Cost * Amortization Multiplier) +

(Sensor Install & Remove Cost) +

((Sensor Cost + Sensor Install & Remove Cost) *

(Sensor Maintenance Multiplier))

The amortization multiplier for each class of measurement method is listed in Table A5-1, and the sensor maintenance multiplier is discussed under Column (6).

The amortized DAS cost is computed as follows. The first step is to compute the DAS cost per active channel. An active channel is one that is connected to a sensor. This cost is computed as follows:

DAS Cost Per Channel
= DAS Cost / (Channel Capacity * Fill Fraction)

The channel capacity and fill fractions for each type of DAS are shown in the table below. The DAS installation and removal costs per channel can be computed in a similar fashion.

TABLE A5-3
Channel Capacity and Fill Fraction by DAS Type

DAS Type	Channel Capacity	Fill Fraction
1	1	1.00
2	4	1.00
3	8	0.75
4	16	0.50
5	1	1.00

The amortized DAS cost per channel can be computed as follows:

Amortized DAS Cost Per Channel
=(DAS Cost Per Channel * Amortization Multiplier) +

DAS Install & Remove Cost Per Channel +

((DAS Cost Per Channel + DAS Install & Remove Cost Per Channel) *

DAS Maintenance Multiplier))

The DAS maintenance multiplier is as discussed under Column 9.

The total amortized cost for each measurement method is then computed by summing the amortized sensor cost and the amortized DAS cost per channel. Column 10 contains the lowest value for this cost based on the low cost estimates in Columns 4a, 5a, 6a, 7a, and 9a. Column 11 contains the highest value for this cost based on the high cost estimates in Columns 4b, 5b, 6b, 7b, and 9b.

A5.4 Excluded Costs. The total amortized costs of specific measurement methods shown in the A5.6.1 Table of Site Specific Measurement Methods do not account for certain costs that will be encountered in conducting a monitoring project. These excluded cost categories are those that depend on specific features of a project's design and the characteristics of the customers who are included in the study. The excluded cost categories include the following:

1. Customer relations.
2. Monitoring plan.
3. Travel.
4. Database design and development.
5. Data polling and communications.
6. Data verification.
7. Data analysis and reporting.

As a general rule-of-thumb, it can be assumed that the total of all of these excluded costs will exceed the costs for purchasing, installing, and maintaining the measurement equipment and should be explicitly budgeted.

A5.5 Impact of Sampling on Measurement Cost and Error. Any project that evaluates savings over a period that is longer than the monitoring period is affected by sampling time. A number of the measurement methods described in the A5.6.1 Table of Site Specific Measurement Methods rely on physical measurements of some duration. Other projects may involve samples of devices, e.g., a random sample of one or two lighting fixtures drawn from a list of all lighting fixtures.

When time is sampled, the physical measurements taken in a short period must be extended to reach a conclusion about the entire period of the impact evaluation, typically a year. When devices are sampled, the physical measurements taken for a few devices must be extended to reach a conclusion about the impact of the program on all affected devices.

There can be considerable benefits associated with sampling time. The primary benefit is the potential reduction in equipment costs that comes from being able to share equipment across a number of customer sites. Cost savings for some monitoring project designs may not be great, especially if multiple short-term measurement periods are needed, as in the case of some pre/post evaluations, to obtain the required measurements. But for some project designs the savings can be substantial. However, the benefit of lower costs has to be balanced against the effect of time sampling on overall measurement error.

The impact of time sampling on measurement error depends on how much the quantities being measured vary with time. In particular, the project designer must be concerned about how different the short-term measurement period is from the typical or average condition for a specific customer. There are a number of possible sources of information on the likely degree of variability for particular measurements. There is a growing body of long-term monitoring results. These results can provide excellent estimates of variability. Some clues about variability can be deduced from the physical properties of the system to be measured. For example, HVAC system loads are known to determined by weather conditions and thus can be assumed to be highly variable. Still more information about potential variability can be assembled by examining the controls that affect the systems being measured. The nature of the controls, e.g., manual or automated, may determine the level of variability.

In some cases, the magnitude of the error associated with sampling time can be trivial. For example, consider the case of outdoor lighting that is on a time-clock. If the time-clock is functioning and dictates the same schedule each week, then measurements for any week of the year will be nearly identical to the average of the entire year. At the other extreme, the effects of sampling time can be large. Examples of particularly bad situations are: (1) estimating electric use for cooling in an office building by taking one week of measurements during a period when temperatures are mild, such as in the late fall; (2) estimating lighting loads for a school based on a one-week measurement taken during summer recess. At first glance these bad situations seem easy to avoid. However, if a project has to be performed during a specific period and equipment must be shared, it is easy to create situations where such measurements will be all that is possible.

In balancing the possible effects on measurement error against the possible benefits of lower measurement costs, the project designer must consider one other factor. Any project that samples time must also develop a model for extending the results of the physical measurements to the period of interest. In some cases, a very simple model is adequate. In other cases, complex models will be required. The labor costs and complexity of this extrapolation may in some cases overwhelm the benefits from the measurement cost savings.

Monitoring projects may also involve sampling devices. This may be done in addition to sampling time or as the only sampling activity. As in the case of sampling time, sampling devices may yield benefits associated with reduced measurement costs. Further, in some cases a device-sampling approach may be the only technically or economically feasible approach to accomplishing the required physical measurements. For example, it would be cost prohibitive, and probably unfeasible from the perspective of impacts on the participating customers, to take true power measurements for all lighting fixtures found in the homes of participants in an efficient lighting program. Instead, run-time metering of sampled fixtures must be used in order to control costs and reduce the intrusion of the measurements into the lives of the participants.

The magnitude of the error associated with device sampling is determined by the degree of uniformity of the devices being sampled. Devices that have both a uniform schedule of operation and a uniform capacity can be sampled without introducing significant errors. When devices are not uniform, it is possible to design the sample to account for the major sources of variability. In general this involves forming clusters of similar devices and sampling one or more devices from each cluster. For example, lighting fixtures in an office building will vary with respect to both their schedule of operation and their capacity. Fixtures can be grouped based on spot measurements of capacity. They can also be grouped by considering the types of spaces in the building, e.g., hallways, offices, and conference rooms, and the control systems, e.g., two-level perimeter zone lighting controls. Even in a complex office building, it is possible to sample a relatively small number of fixtures and accurately represent the typical energy use of all fixtures in the building.

In conclusion, the effects of both time and device sampling can be significant. These techniques may provide substantial benefits due to reduced measurement costs. However, they can significantly increase measurement uncertainty. Caution must be exercised in using either of these techniques. Further, the designers of projects that use these techniques must plan to develop reliable methods for extending the physical measurements from the sample to the period or population of devices affected.

A5.6 Site Specific Measurement Methods

A5.6.1 Table of Site Specific Measurement Methods. The Table of Site Specific Measurement Methods is presented on the following pages. Each column of this table is defined in A5.3, “Measurement Cost.” Further information on each method is provided in A5.6.2, “Technical Notes for Table of Site Specific Measurement Methods.” The technical notes further describe the physical properties, installation procedures, and expected range of instrument system error associated with each unique type of sensor referenced in A5.6.1.

A5.6.2 Technical Notes for Table of Site Specific Measurement Methods

A5.6.2.1 Electric Usage

Technical Note #1: Existing Energy Meter

- Sensor Installation and Maintenance: Instrumentation technician, one-half hour; zero maintenance.
- Measurement Procedures: The existing utility meter is manually read as required by the experimental design.
- Instrument System Error: 1%.
- Comments: One-time utility meter readings are often a component of various technology performance evaluations. This approach can sometimes be used as an alternative to portable watt meter readings.

Technical Note #2: Existing Demand Meter

- Sensor Installation and Maintenance: One-half hour for instrumentation technician; zero maintenance.
- Measurement Procedures: Read existing utility demand meter.
- Instrument System Error: 1%.
- Comments: Locating the meter is sometimes the biggest challenge in this measurement.

Technical Note #3: Portable Watt Meter

- Sensor Output: Digital display
- Sensor Installation and Maintenance: One-half hour for instrumentation technician, mainly to set up for measurement; normal maintenance.
- Measurement Procedures: Use “clamp-on” watt meter.
- Instrument System Error: 1% to 5%.
- Comments: Reference voltage typically obtained by installing spring clips on electrical panel lugs. Should one of the clips become disconnected and go to ground in the process of obtaining a measurement, a potentially

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized Cost per Measurement Point ($)	
Class of Method / Application / Sensor Type	DAS	Tech.	Purchase (4)		Install & Remove (5)		Maintenance (6)		Purchase (7)		Install &	Maintenance (9)			
(1)	Type (2)	Note (3)	Low (4.a)	High (4.b)	Low (5.a)	High (5.b)	Low (6.a)	High (6.b)	Low (7.a)	High (7.b)	Remove (8)	Low (9.a)	High (9.b)	Low (10)	High (11)
Measurement Type: Electric Consumption															
Spot Measurement															
Whole Building or Service															
Existing Energy Meter	1	1	0	0	28	28	0	0	0	0	0	0	0	28	28
Existing Demand Meter	1	2	0	0	28	28	0	0	0	0	0	0	0	28	28
Component, Device, or Appliance															
Portable Watt Meter	1	3	440	11,000	28	28	0	2	0	0	0	0	0	32	139
Demand Meter	1	4	500	1,000	0	0	0	0	0	0	0	0	0	5	10
Short-Term, Shared Equipment															
Whole Building or Service															
IR Pulse Detector	2	5	83	83	110	110	2	2	880	2,200	440	8	12	306	392
	3	5	83	83	110	110	2	2	1,650	4,400	660	8	14	306	435
	4	5	83	83	110	110	2	2	2,950	3,600	880	6	8	248	306
Whole Bldg or Service - Existing CTs															
Shunted CTs on Secondaries	4	6	275	330	55	55	2	2	2,950	3,600	880	36	69	876	1,583
Whole Bldg or Service - New Meter															
Shunted CTs	4	7	275	660	220	220	4	5	2,950	3,600	880	36	69	1,043	1,834
Component, Device, or Appliance															
Portable Recording Watt Meter	5	8	7,700	11,000	55	55	25	35	0	0	0	0	0	2,005	2,840
Portable Cumulative Run-Time Meter	5	9	150	250	55	55	1	1	0	0	0	0	0	94	119
Portable Time-of-Use Run-Time Meter	5	10	450	600	55	55	2	3	0	0	0	0	0	170	208
Shunted CTs	4	11	250	660	220	220	4	5	2,950	3,600	880	25	69	806	1,834

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized	
Class of Method			Purchase		Install & Remove		Maintenance		Purchase			Maintenance		Cost per Measure-ment Point ($)	
Application	DAS	Tech.	(4)		(5)		(6)		(7)		Install &	(9)			
Sensor Type	Type	Note	Low	High	Low	High	Low	High	Low	High	Remove	Low	High	Low	High
(1)	(2)	(3)	(4.a)	(4.b)	(5.a)	(5.b)	(6.a)	(6.b)	(7.a)	(7.b)	(8)	(9.a)	(9.b)	(10)	(11)
Short-Term, Devoted Equipment															
Whole Building or Service															
IR Pulse Detector	2	5	83	83	110	110	2	2	880	2,200	440	17	33	541	888
	3	5	83	83	110	110	2	2	1,650	4,400	660	17	41	541	1,061
	4	5	83	83	110	110	2	2	2,950	3,600	880	14	25	484	715
Whole Bldg or Service - Existing CTs															
Shunted CTs on Secondaries	4	6	275	330	220	220	6	7	2,950	3,600	880	36	69	1,252	2,001
Whole Bldg or Service - New Meter															
Shunted CTs	4	7	275	660	220	220	6	11	2,950	3,600	880	36	69	1,252	2,335
Component, Device, or Appliance															
Portable Cumulative Run-Time Meter	5	9	150	250	55	55	3	4	0	0	0	0	0	208	309
Portable Time-of-Use Run-Time Meter	5	10	450	600	55	55	6	8	0	0	0	0	0	511	663
Shunted CTs	4	11	250	660	220	220	6	11	2,950	3,600	880	25	69	996	2,335
Long-Term, Devoted Equipment															
Whole Building or Service															
IR Pulse Detector	2	5	83	83	110	110	10	10	880	2,200	440	17	33	549	895
	3	5	83	83	110	110	10	10	1,650	4,400	660	17	41	549	1,068
	4	5	83	83	110	110	10	10	2,950	3,600	880	14	25	491	722
Pulse Splitter	2	12	330	550	0	0	17	28	880	2,200	440	17	33	693	1,271
	3	12	330	550	0	0	17	28	1,650	4,400	660	17	41	693	1,444
	4	12	330	550	0	0	17	28	2,950	3,600	880	14	25	635	1,097
Whole Bldg or Service - Existing CTs															
Shunted CTs on Secondaries	4	6	275	330	220	220	25	28	2,950	3,600	880	36	69	1,271	2,021
CTs on Secondaries & Watt Transducer	2	13	600	700	440	880	52	79	880	2,200	440	17	33	1,439	2,352
	3	13	600	700	440	880	52	79	1,650	4,400	660	17	41	1,439	2,525
	4	13	600	700	440	880	52	79	2,950	3,600	880	14	25	1,381	2,179

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized	
Class of Method / Application / Sensor Type (1)	DAS Type (2)	Tech. Note (3)	Purchase (4) Low (4.a)	Purchase (4) High (4.b)	Install & Remove (5) Low (5.a)	Install & Remove (5) High (5.b)	Maintenance (6) Low (6.a)	Maintenance (6) High (6.b)	Purchase (7) Low (7.a)	Purchase (7) High (7.b)	Install & Remove (8)	Maintenance (9) Low (9.a)	Maintenance (9) High (9.b)	Cost per Measurement Point ($) Low (10)	Cost per Measurement Point ($) High (11)
Air in Ducts															
Electronic Temperature Sensor Array	3	34	75	200	220	440	15	32	1,650	4,400	660	17	41	656	1,538
	4	34	75	200	220	440	15	32	2,950	3,600	880	14	25	599	1,192
Measurement Type: Relative Humidity															
Spot Measurement															
Ambient Indoor															
Sling Psychrometer	1	37	75	75	14	14	1	1	0	0	0	0	0	16	16
Portable Electronic RH Meter	1	38	350	800	14	14	5	10	0	0	0	0	0	22	32
Ambient Outdoor															
Sling Psychrometer	1	39	75	75	14	14	1	1	0	0	0	0	0	16	16
Portable Electronic RH Meter	1	40	350	800	14	14	5	10	0	0	0	0	0	22	32
Short-Term, Shared Equipment															
Ambient Indoor															
Electronic RH Sensor	3	41	200	550	110	330	4	11	1,650	4,400	660	8	14	337	782
	4	41	200	550	110	330	4	11	2,950	3,600	880	6	8	279	652
Ambient Outdoor															
Electronic RH Sensor	3	42	350	700	110	330	6	13	1,650	4,400	660	8	14	377	821
	4	42	350	700	110	330	6	13	2,950	3,600	880	6	8	319	691
Short-Term, Devoted Equipment															
Ambient Indoor															
Electronic RH Sensor	3	41	200	550	110	330	4	11	1,650	4,400	660	17	41	660	1,757
	4	41	200	550	110	330	4	11	2,950	3,600	880	14	25	603	1,411
Ambient Outdoor															
Electronic RH Sensor	3	42	350	700	110	330	6	13	1,650	4,400	660	17	41	812	1,909
	4	42	350	700	110	330	6	13	2,950	3,600	880	14	25	755	1,563

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized Cost per Measurement Point ($)	
Class of Method / Application / Sensor Type	DAS	Tech.	Purchase (4)		Install & Remove (5)		Maintenance (6)		Purchase (7)		Install &	Maintenance (9)			
	Type	Note	Low	High	Low	High	Low	High	Low	High	Remove	Low	High	Low	High
(1)	(2)	(3)	(4.a)	(4.b)	(5.a)	(5.b)	(6.a)	(6.b)	(7.a)	(7.b)	(8)	(9.a)	(9.b)	(10)	(11)
Short-Term, Shared Equipment															
Whole Building or Service															
Pulse Initiator	2	19	150	450	0	0	2	6	880	2,200	440	8	12	213	378
	3	19	150	450	0	0	2	6	1,650	4,400	660	8	14	213	421
	4	19	150	450	0	0	2	6	2,950	3,600	880	6	8	155	291
Device or Appliance															
New Pulse Meter	2	20	400	800	0	0	5	10	880	2,200	440	8	12	278	470
	3	20	400	800	0	0	5	10	1,650	4,400	660	8	14	278	513
	4	20	400	800	0	0	5	10	2,950	3,600	880	6	8	221	383
Run-Time Sensor	2	21	55	55	220	220	3	3	880	2,200	440	8	12	410	497
	3	21	55	55	220	220	3	3	1,650	4,400	660	8	14	410	540
	4	21	55	55	220	220	3	3	2,950	3,600	880	6	8	353	410
Short-Term, Devoted Equipment															
Whole Building or Service															
Pulse Initiator	2	19	150	450	0	0	2	6	880	2,200	440	17	33	498	1,149
	3	19	150	450	0	0	2	6	1,650	4,400	660	17	41	498	1,322
	4	19	150	450	0	0	2	6	2,950	3,600	880	14	25	441	975
Device or Appliance															
New Pulse Meter	2	20	400	800	0	0	5	10	880	2,200	440	17	33	752	1,503
	3	20	400	800	0	0	5	10	1,650	4,400	660	17	41	752	1,676
	4	20	400	800	0	0	5	10	2,950	3,600	880	14	25	694	1,330
Run-Time Sensor	2	21	55	55	220	220	3	3	880	2,200	440	17	33	625	971
	3	21	55	55	220	220	3	3	1,650	4,400	660	17	41	625	1,145
	4	21	55	55	220	220	3	3	2,950	3,600	880	14	25	567	798

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized Cost per Measurement Point ($)	
Class of Method / Application / Sensor Type	DAS Type	Tech. Note	Purchase (4)		Install & Remove (5)		Maintenance (6)		Purchase (7)		Install & Remove	Maintenance (9)			
(1)	(2)	(3)	Low (4.a)	High (4.b)	Low (5.a)	High (5.b)	Low (6.a)	High (6.b)	Low (7.a)	High (7.b)	(8)	Low (9.a)	High (9.b)	Low (10)	High (11)
Long-Term, Devoted Equipment															
Whole Building or Service															
Pulse Initiator	2	19	150	450	0	0	8	23	880	2,200	440	17	33	504	1,166
	3	19	150	450	0	0	8	23	1,650	4,400	660	17	41	504	1,339
	4	19	150	450	0	0	8	23	2,950	3,600	880	14	25	446	992
Device or Appliance															
New Pulse Meter	2	20	400	800	0	0	20	40	880	2,200	440	17	33	767	1,533
	3	20	400	800	0	0	20	40	1,650	4,400	660	17	41	767	1,706
	4	20	400	800	0	0	20	40	2,950	3,600	880	14	25	709	1,360
Run-Time Sensor	2	21	55	55	220	220	14	14	880	2,200	440	17	33	635	982
	3	21	55	55	220	220	14	14	1,650	4,400	660	17	41	635	1,155
	4	21	55	55	220	220	14	14	2,950	3,600	880	14	25	578	809
Measurement Type: Temperature															
Spot Measurement															
Ambient Indoor															
Portable Electronic Thermometer	1	22	150	220	14	14	2	3	0	0	0	0	0	17	19
Ambient Outdoor															
Portable Electronic Thermometer	1	23	165	350	14	14	2	5	0	0	0	0	0	18	22
Domestic Water															
Portable Electronic Thermometer	1	24	165	350	14	14	2	5	0	0	0	0	0	18	22
Air in Ducts															
Portable Electronic Thermometer	1	25	250	500	28	28	3	7	0	0	0	0	0	33	39

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized	
Class of Method			Purchase (4)		Install & Remove (5)		Maintenance (6)		Purchase (7)		Install &	Maintenance (9)		Cost per Measurement Point ($)	
Application / Sensor Type (1)	DAS Type (2)	Tech. Note (3)	Low (4.a)	High (4.b)	Low (5.a)	High (5.b)	Low (6.a)	High (6.b)	Low (7.a)	High (7.b)	Remove (8)	Low (9.a)	High (9.b)	Low (10)	High (11)
Short-Term, Shared Equipment															
Ambient Indoor															
Portable Recording Elec. Thermometer	5	26	400	1,000	110	110	6	14	0	0	0	0	0	216	374
Electronic Temperature Sensor	2	27	25	250	110	110	2	5	880	2,200	440	8	12	291	437
	3	27	25	250	110	110	2	5	1,650	4,400	660	8	14	291	480
	4	27	25	250	110	110	2	5	2,950	3,600	880	6	8	233	350
Ambient Outdoor															
Portable Recording Elec. Thermometer	5	28	425	1,000	110	110	7	14	0	0	0	0	0	223	374
Electronic Temperature Sensor	3	29	50	250	110	110	2	5	1,650	4,400	660	8	14	298	480
	4	29	50	250	110	110	2	5	2,950	3,600	880	6	8	240	350
Domestic Water															
Surface-Mounted Elec. Temp. Sensor	3	30	50	100	110	220	2	4	1,650	4,400	660	8	14	298	552
	4	30	50	100	110	220	2	4	2,950	3,600	880	6	8	240	422
Electronic Temp. Sensor & Thermowell	3	31	100	200	220	220	4	5	1,650	4,400	660	8	14	422	578
	4	31	100	200	220	220	4	5	2,950	3,600	880	6	8	365	449
HVAC Water in Pipe															
Surface-Mounted Elec. Temp. Sensor	3	32	75	300	110	220	2	7	1,650	4,400	660	8	14	304	605
	4	32	75	300	110	220	2	7	2,950	3,600	880	6	8	247	475
Refrigerant in Pipe															
Surface-Mounted Elec. Temp. Sensor	3	33	75	300	110	220	2	7	1,650	4,400	660	8	14	304	605
	4	33	75	300	110	220	2	7	2,950	3,600	880	6	8	247	475
Air in Ducts															
Electronic Temperature Sensor Array	3	34	75	200	220	440	4	8	1,650	4,400	660	8	14	416	801
	4	34	75	200	220	440	4	8	2,950	3,600	880	6	8	358	671

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized	
Class of Method / Application / Sensor Type (1)	DAS Type (2)	Tech. Note (3)	Purchase (4) Low (4.a)	Purchase (4) High (4.b)	Install & Remove (5) Low (5.a)	Install & Remove (5) High (5.b)	Maintenance (6) Low (6.a)	Maintenance (6) High (6.b)	Purchase (7) Low (7.a)	Purchase (7) High (7.b)	Install & Remove (8)	Maintenance (9) Low (9.a)	Maintenance (9) High (9.b)	Cost per Measurement Point ($) Low (10)	Cost per Measurement Point ($) High (11)
Short-Term, Devoted Equipment															
Ambient Indoor															
Portable Recording Elect. Thermometer	5	26	400	1,000	110	110	6	14	0	0	0	0	0	516	1,124
Electronic Temperature Sensor	2	27	25	250	110	110	2	5	880	2,200	440	17	33	483	1,058
	3	27	25	250	110	110	2	5	1,650	4,400	660	17	41	483	1,231
	4	27	25	250	110	110	2	5	2,950	3,600	880	14	25	425	884
Ambient Outdoor															
Portable Recording Elec. Thermometer	5	28	425	1,000	110	110	7	14	0	0	0	0	0	542	1,124
Electronic Temperature Sensor	3	29	50	250	110	110	2	5	1,650	4,400	660	17	41	509	1,231
	4	29	50	250	110	110	2	5	2,950	3,600	880	14	25	451	884
Domestic Water															
Surface-Mounted Elec. Temp. Sensor	3	30	50	100	110	220	2	4	1,650	4,400	660	17	41	509	1,190
	4	30	50	100	110	220	2	4	2,950	3,600	880	14	25	451	844
Electronic Temp. Sensor & Thermowell	3	31	100	200	220	220	4	5	1,650	4,400	660	17	41	671	1,292
	4	31	100	200	220	220	4	5	2,950	3,600	880	14	25	613	945
HVAC Water in Pipe															
Surface-Mounted Elec. Temp. Sensor	3	32	75	300	110	220	2	7	1,650	4,400	660	17	41	534	1,393
	4	32	75	300	110	220	2	7	2,950	3,600	880	14	25	476	1,046
Refrigerant in Pipe															
Surface-Mounted Elec. Temp. Sensor	3	33	75	300	110	220	2	7	1,650	4,400	660	17	41	534	1,393
	4	33	75	300	110	220	2	7	2,950	3,600	880	14	25	476	1,046
Air in Ducts															
Electronic Temperature Sensor Array	3	34	75	200	220	440	4	8	1,650	4,400	660	17	41	645	1,514
	4	34	75	200	220	440	4	8	2,950	3,600	880	14	25	587	1,168

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized Cost per Measurement Point ($)	
Class of Method / Application / Sensor Type	DAS Type	Tech. Note	Purchase (4)		Install & Remove (5)		Maintenance (6)		Purchase (7)		Install & Remove	Maintenance (9)			
(1)	(2)	(3)	Low (4.a)	High (4.b)	Low (5.a)	High (5.b)	Low (6.a)	High (6.b)	Low (7.a)	High (7.b)	(8)	Low (9.a)	High (9.b)	Low (10)	High (11)
Long-Term, Devoted Equipment															
Ambient Indoor															
Electronic Temperature Sensor	2	27	25	250	110	110	7	18	880	2,200	440	17	33	488	1,071
	3	27	25	250	110	110	7	18	1,650	4,400	660	17	41	488	1,244
	4	27	25	250	110	110	7	18	2,950	3,600	880	14	25	431	898
Ambient Outdoor															
Electronic Temperature Sensor	3	29	50	250	110	110	8	18	1,650	4,400	660	17	41	515	1,244
	4	29	50	250	110	110	8	18	2,950	3,600	880	14	25	457	898
Domestic Water															
Surface-Mounted Elec. Temp. Sensor	3	30	50	100	110	220	8	16	1,650	4,400	660	17	41	515	1,202
	4	30	50	100	110	220	8	16	2,950	3,600	880	14	25	457	856
Electronic Temp. Sensor & Thermowell	3	31	100	200	220	220	16	21	1,650	4,400	660	17	41	683	1,307
	4	31	100	200	220	220	16	21	2,950	3,600	880	14	25	625	961
HVAC Water in Pipe															
Surface-Mounted Elec. Temp. Sensor	3	32	75	300	110	220	9	26	1,650	4,400	660	17	41	541	1,412
	4	32	75	300	110	220	9	26	2,950	3,600	880	14	25	483	1,066
Electronic Temp. Sensor & Thermowell	3	35	275	500	220	220	25	36	1,650	4,400	660	17	41	866	1,622
	4	35	275	500	220	220	25	36	2,950	3,600	880	14	25	809	1,276
Refrigerant in Pipe															
Surface-Mounted Elec. Temp. Sensor	3	33	75	300	110	220	9	26	1,650	4,400	660	17	41	541	1,412
	4	33	75	300	110	220	9	26	2,950	3,600	880	14	25	483	1,066
Electronic Temp. Sensor & Thermowell	3	36	275	550	440	440	36	50	1,650	4,400	660	17	41	1,097	1,906
	4	36	275	550	440	440	36	50	2,950	3,600	880	14	25	1,040	1,559

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized Cost per Measurement Point ($)	
Class of Method / Application / Sensor Type	DAS	Tech.	Purchase (4)		Install & Remove (5)		Maintenance (6)		Purchase (7)		Install &	Maintenance (9)			
	Type	Note	Low	High	Low	High	Low	High	Low	High	Remove	Low	High	Low	High
(1)	(2)	(3)	(4.a)	(4.b)	(5.a)	(5.b)	(6.a)	(6.b)	(7.a)	(7.b)	(8)	(9.a)	(9.b)	(10)	(11)
Air in Ducts															
Electronic Temperature Sensor Array	3	34	75	200	220	440	15	32	1,650	4,400	660	17	41	656	1,538
	4	34	75	200	220	440	15	32	2,950	3,600	880	14	25	599	1,192
Measurement Type: Relative Humidity															
Spot Measurement															
Ambient Indoor															
Sling Psychrometer	1	37	75	75	14	14	1	1	0	0	0	0	0	16	16
Portable Electronic RH Meter	1	38	350	800	14	14	5	10	0	0	0	0	0	22	32
Ambient Outdoor															
Sling Psychrometer	1	39	75	75	14	14	1	1	0	0	0	0	0	16	16
Portable Electronic RH Meter	1	40	350	800	14	14	5	10	0	0	0	0	0	22	32
Short-Term, Shared Equipment															
Ambient Indoor															
Electronic RH Sensor	3	41	200	550	110	330	4	11	1,650	4,400	660	8	14	337	782
	4	41	200	550	110	330	4	11	2,950	3,600	880	6	8	279	652
Ambient Outdoor															
Electronic RH Sensor	3	42	350	700	110	330	6	13	1,650	4,400	660	8	14	377	821
	4	42	350	700	110	330	6	13	2,950	3,600	880	6	8	319	691
Short-Term, Devoted Equipment															
Ambient Indoor															
Electronic RH Sensor	3	41	200	550	110	330	4	11	1,650	4,400	660	17	41	660	1,757
	4	41	200	550	110	330	4	11	2,950	3,600	880	14	25	603	1,411
Ambient Outdoor															
Electronic RH Sensor	3	42	350	700	110	330	6	13	1,650	4,400	660	17	41	812	1,909
	4	42	350	700	110	330	6	13	2,950	3,600	880	14	25	755	1,563

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized Cost per Measurement Point ($)	
Class of Method / Application / Sensor Type	DAS Type	Tech. Note	Purchase (4)		Install & Remove (5)		Maintenance (6)		Purchase (7)		Install & Remove	Maintenance (9)			
(1)	(2)	(3)	Low (4.a)	High (4.b)	Low (5.a)	High (5.b)	Low (6.a)	High (6.b)	Low (7.a)	High (7.b)	(8)	Low (9.a)	High (9.b)	Low (10)	High (11)
Long-Term, Devoted Equipment															
Ambient Indoor															
Electronic RH Sensor	3	41	200	550	110	330	16	44	1,650	4,400	660	17	41	672	1,790
	4	41	200	550	110	330	16	44	2,950	3,600	880	14	25	614	1,444
Ambient Outdoor															
Electronic RH Sensor	3	42	350	700	110	330	23	52	1,650	4,400	660	17	41	830	1,948
	4	42	350	700	110	330	23	52	2,950	3,600	880	14	25	772	1,601
Electronic Dew Point Sensor	3	43	1,000	1,500	220	440	61	97	1,650	4,400	660	660	660	2,271	3,522
	4	43	1,000	1,500	220	440	61	97	2,950	3,600	880	660	660	2,216	3,192
Measurement Type: Flow Rate															
Spot Measurement															
Domestic Water															
Bucket/Stopwatch	1	44	50	100	28	28	1	2	0	0	0	0	0	29	30
Domestic Hot Water															
Bucket/Stopwatch	1	45	50	100	28	28	1	2	0	0	0	0	0	29	30
HVAC Hydronic Fluids															
Portable Ultrasonic Flow Meter	1	46	5,000	12,000	55	55	63	151	0	0	0	0	0	168	326
Refrigerant Liquid															
Portable Ultrasonic Flow Meter	1	47	5,000	12,000	55	55	63	151	0	0	0	0	0	168	326
Air in Ducts															
Portable Flow Measurement Probe	1	48	350	1,100	28	28	5	14	0	0	0	0	0	36	53
Flow Hood	1	49	1,400	2,200	28	28	18	28	0	0	0	0	0	59	77
Pressurization/Depressurization Test	5	50	1,200	1,600	110	110	16	21	0	0	0	0	0	138	147

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized	
Class of Method / Application / Sensor Type (1)	DAS Type (2)	Tech. Note (3)	Purchase (4) Low (4.a)	Purchase (4) High (4.b)	Install & Remove (5) Low (5.a)	Install & Remove (5) High (5.b)	Maintenance (6) Low (6.a)	Maintenance (6) High (6.b)	Purchase (7) Low (7.a)	Purchase (7) High (7.b)	Install & Remove (8)	Maintenance (9) Low (9.a)	Maintenance (9) High (9.b)	Cost per Measurement Point ($) Low (10)	Cost per Measurement Point ($) High (11)
Short-Term, Shared Equipment															
Domestic Water															
Portable Flow Meter	2	51	100	100	28	28	2	2	0	0	440	0	0	54	54
Domestic Hot Water															
Portable Flow Meter	1	51	100	100	28	28	2	2	0	0	0	0	0	54	54
Short-Term, Devoted Equipment															
Domestic Water															
Portable Flow Meter	3	51	100	100	28	28	2	2	0	0	660	0	0	129	129
Domestic Hot Water															
Portable Flow Meter	1	51	100	100	28	28	2	2	0	0	0	0	0	129	129
Long-Term, Devoted Equipment															
Domestic Water															
Portable Flow Meter	4	51	100	100	28	28	6	6	0	0	880	0	0	134	134
Accumulating Flow Meter	1	52	150	250	110	110	13	18	0	0	0	0	0	273	378
Pulse Flow Meter	2	53	175	300	220	220	20	26	880	2,200	440	17	33	761	1,239
	3	53	175	300	220	220	20	26	1,650	4,400	660	17	41	761	1,412
	4	53	175	300	220	220	20	26	2,950	3,600	880	14	25	704	1,066
Domestic Hot Water															
Portable Flow Meter	1	51	100	100	28	28	6	6	0	0	0	0	0	134	134
Accumulating Flow Meter	1	54	150	250	110	110	13	18	0	0	0	0	0	273	378
Pulse Flow Meter	2	55	175	300	220	220	20	26	880	2,200	440	17	33	761	1,239
	3	55	175	300	220	220	20	26	1,650	4,400	660	17	41	761	1,412
	4	55	175	300	220	220	20	26	2,950	3,600	880	14	25	704	1,066

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized	
Class of Method			Purchase (4)		Install & Remove (5)		Maintenance (6)		Purchase (7)		Install &	Maintenance (9)		Cost per Measurement Point ($)	
Application / Sensor Type (1)	DAS Type (2)	Tech. Note (3)	Low (4.a)	High (4.b)	Low (5.a)	High (5.b)	Low (6.a)	High (6.b)	Low (7.a)	High (7.b)	Remove (8)	Low (9.a)	High (9.b)	Low (10)	High (11)
HVAC Hydronic Fluids															
In-line or Insertion Flow Meter	2	56	1,000	2,500	440	440	72	147	880	2,200	440	33	66	1,875	3,813
	3	56	1,000	2,500	440	440	72	147	1,650	4,400	660	33	83	1,875	3,995
	4	56	1,000	2,500	440	440	72	147	2,950	3,600	880	28	50	1,815	3,632
Refrigerant Liquid															
In-line or Insertion Flow Meter	2	57	1,000	2,500	440	660	72	158	880	2,200	440	17	33	1,859	4,011
	3	57	1,000	2,500	440	660	72	158	1,650	4,400	660	17	41	1,859	4,184
	4	57	1,000	2,500	440	660	72	158	2,950	3,600	880	14	25	1,801	3,838
Air in Ducts															
Flow Measurement Array	3	58	1,550	2,000	440	660	100	133	1,650	4,400	660	33	83	2,453	3,701
	4	58	1,550	2,000	440	660	100	133	2,950	3,600	880	28	50	2,392	3,338
Refrigerant Vapor															
Flow Measurement Array	3	59	2,000	3,500	440	660	122	208	1,650	4,400	660	33	83	2,925	5,276
	4	59	2,000	3,500	440	660	122	208	2,950	3,600	880	28	50	2,865	4,913
Measurement Type: BTU Metering															
Long-Term, Devoted Equipment															
All Applications															
Electronic BTU Meter	2	60	600	2,000	220	220	41	111	880	2,200	440	17	33	1,208	3,024
	3	60	600	2,000	220	220	41	111	1,650	4,400	660	17	41	1,208	3,197
	4	60	600	2,000	220	220	41	111	2,950	3,600	880	14	25	1,150	2,851
Data Logger - Real-Time Math	3	61	0	0	220	440	11	22	1,650	4,400	660	17	41	578	1,328
	4	61	0	0	220	440	11	22	2,950	3,600	880	14	25	520	982

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized Cost per Measurement Point ($)	
Class of Method / Application / Sensor Type	DAS Type	Tech. Note	Purchase (4)		Install & Remove (5)		Maintenance (6)		Purchase (7)		Install & Remove	Maintenance (9)			
(1)	(2)	(3)	Low (4.a)	High (4.b)	Low (5.a)	High (5.b)	Low (6.a)	High (6.b)	Low (7.a)	High (7.b)	(8)	Low (9.a)	High (9.b)	Low (10)	High (11)
Measurement Type: Non-Mechanical Ventilation															
Spot Measurement															
Instantaneous Ventilation Rate															
SF6	1	62	200	400	165	165	5	7	0	0	0	0	0	172	176
Average Ventilation Rate															
PFT	1	63	200	200	110	110	4	4	0	0	0	0	0	116	116
Inferred Infiltration Rate															
Blower Door	1	64	1,500	2,750	110	110	20	36	0	0	0	0	0	145	173
Measurement Type: Pressure															
Long-Term, Devoted Equipment															
Air in Ducts															
Pressure Transmitter	3	65	150	700	220	440	19	57	1,650	4,400	660	17	41	735	2,063
	4	65	150	700	220	440	19	57	2,950	3,600	880	14	25	677	1,717
Refrigerant Vapor															
Pressure Transmitter	3	66	350	900	220	440	29	67	1,650	4,400	660	17	41	945	2,273
	4	66	350	900	220	440	29	67	2,950	3,600	880	14	25	887	1,927
Liquid in Pipe															
Pressure Transducer	3	67	600	1,200	220	440	41	82	1,650	4,400	660	17	41	1,208	2,588
	4	67	600	1,200	220	440	41	82	2,950	3,600	880	14	25	1,150	2,242
Measurement Type: Solar Radiation															
Short-Term, Shared Equipment															
Direct Solar Radiation															
Pyrheliometer	3	68	9,000	10,500	440	440	118	137	1,650	4,400	660	17	29	2,990	3,519
	4	68	9,000	10,500	440	440	118	137	2,950	3,600	880	11	17	2,929	3,383

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized Cost per Measurement Point ($)	
Class of Method / Application / Sensor Type	DAS Type	Tech. Note	Purchase (4)		Install & Remove (5)		Maintenance (6)		Purchase (7)		Install & Remove	Maintenance (9)			
(1)	(2)	(3)	Low (4.a)	High (4.b)	Low (5.a)	High (5.b)	Low (6.a)	High (6.b)	Low (7.a)	High (7.b)	(8)	Low (9.a)	High (9.b)	Low (10)	High (11)
Global Radiation															
Pyranometer	3	69	200	1,000	220	220	5	15	1,650	4,400	660	17	29	457	803
	4	69	200	1,000	220	220	5	15	2,950	3,600	880	11	17	396	667
Short-Term, Devoted Equipment															
Direct Solar Radiation															
Pyrheliometer	3	68	9,000	10,500	440	440	118	137	1,650	4,400	660	33	83	9,921	11,984
	4	68	9,000	10,500	440	440	118	137	2,950	3,600	880	28	50	9,861	11,621
Global Radiation															
Pyranometer	3	69	200	1,000	220	220	5	15	1,650	4,400	660	33	83	788	2,143
	4	69	200	1,000	220	220	5	15	2,950	3,600	880	28	50	728	1,780
Long-Term, Devoted Equipment															
Direct Solar Radiation															
Pyrheliometer	3	68	9,000	10,500	440	440	472	547	1,650	4,400	660	33	83	10,275	12,395
	4	68	9,000	10,500	440	440	472	547	2,950	3,600	880	28	50	10,215	12,032
Global Radiation															
Pyranometer	3	69	200	1,000	220	220	21	61	1,650	4,400	660	33	83	804	2,189
	4	69	200	1,000	220	220	21	61	2,950	3,600	880	28	50	744	1,826
Measurement Type: Door Position															
Long-Term, Devoted Equipment															
All Applications															
Contact Closure	2	70	75	75	110	220	9	15	880	2,200	440	17	33	541	1,003
	3	70	75	75	110	220	9	15	1,650	4,400	660	17	41	541	1,176
	4	70	75	75	110	220	9	15	2,950	3,600	880	14	25	483	830
Measurement Type: Production Rate															

Note: Requires Site Specific Measurement Design

Table of Site Specific Measurement Methods

Measurement Methods			Sensor Cost ($)						Data Acquisition System Cost ($)					Total Amortized Cost per Measurement Point ($)	
Class of Method / Application / Sensor Type	DAS Type	Tech. Note	Purchase (4)		Install & Remove (5)		Maintenance (6)		Purchase (7)		Install & Remove	Maintenance (9)			
			Low	High	Low	High	Low	High	Low	High		Low	High	Low	High
(1)	(2)	(3)	(4.a)	(4.b)	(5.a)	(5.b)	(6.a)	(6.b)	(7.a)	(7.b)	(8)	(9.a)	(9.b)	(10)	(11)
Measurement Type: RPM															
Spot Measurement															
All Applications															
Portable Tachometer/Stroboscope	1	71	250	400	28	28	3	5	0	0	0	0	0	33	37
Long-Term, Devoted Equip.															
All Applications															
Electronic RPM Sensor	3	72	300	600	220	440	26	52	1,650	4,400	660	17	41	893	1,958
	4	72	300	600	220	440	26	52	2,950	3,600	880	14	25	835	1,612
Measurement Type: "On Time"															
Short-Term, Shared Equipment															
Device or Appliance															
Status Sensor	2	73	55	55	220	220	3	3	880	2,200	440	8	12	410	497
	3	73	55	55	220	220	3	3	1,650	4,400	660	8	14	410	540
	4	73	55	55	220	220	3	3	2,950	3,600	880	6	8	353	410
Short-Term, Devoted Equipment															
Device or Appliance															
Status Sensor	2	73	55	55	220	220	3	3	880	2,200	440	17	33	625	971
	3	73	55	55	220	220	3	3	1,650	4,400	660	17	41	625	1,145
	4	73	55	55	220	220	3	3	2,950	3,600	880	14	25	567	798
Long-Term, Devoted Equipment															
Device or Appliance															
Status Sensor	2	73	55	55	220	220	14	14	880	2,200	440	17	33	635	982
	3	73	55	55	220	220	14	14	1,650	4,400	660	17	41	635	1,155
	4	73	55	55	220	220	14	14	2,950	3,600	880	14	25	578	809

Table of Site Specific Measurement Methods

Measurement Methods / Class of Method / Application / Sensor Type (1)	DAS Type (2)	Tech. Note (3)	Sensor Cost ($) Purchase (4) Low (4.a)	Sensor Cost ($) Purchase (4) High (4.b)	Install & Remove (5) Low (5.a)	Install & Remove (5) High (5.b)	Maintenance (6) Low (6.a)	Maintenance (6) High (6.b)	Data Acquisition System Cost ($) Purchase (7) Low (7.a)	Purchase (7) High (7.b)	Install & Remove (8)	Maintenance (9) Low (9.a)	Maintenance (9) High (9.b)	Total Amortized Cost per Measurement Point ($) Low (10)	High (11)
Measurement Type: Wind Speed															
Spot Measurement															
All Applications															
Hand Held Anemometer	1	74	60	60	14	14	1	1	0	0	0	0	0	15	15
Short-Term, Shared Equipment															
All Applications															
Recording Anemometer	3	75	350	500	220	440	7	12	1,650	4,400	660	17	29	496	894
	4	75	350	500	220	440	7	12	2,950	3,600	880	11	17	436	758
Short-Term, Devoted Equipment															
All Applications															
Recording Anemometer	3	75	350	500	220	440	7	12	1,650	4,400	660	33	83	940	1,859
	4	75	350	500	220	440	7	12	2,950	3,600	880	28	50	880	1,496
Long-Term, Devoted Equipment															
All Applications															
Recording Anemometer	3	75	350	500	220	440	29	47	1,650	4,400	660	33	83	962	1,895
	4	75	350	500	220	440	29	47	2,950	3,600	880	28	50	901	1,532
Meteorological Grade Recording Anemometer	3	76	1,500	2,500	440	880	97	169	1,650	4,400	660	33	83	2,400	4,457
	4	76	1,500	2,500	440	880	97	169	2,950	3,600	880	28	50	2,340	4,094

hazardous and damaging electrical failure will result.
- Portable watt meter data must be combined with measurements of operating hours (see notes 9 and 10) to compute electricity use.

Technical Note #4: Demand Meter

- Sensor Installation and Maintenance: Installation costs included; zero maintenance.
- Measurement Procedures: Typically installed by utility meter department personnel.
- Instrument System Error: 1%.
- Comments: Approach provides instantaneous demand only, interval demand obtained using use measurement approaches.

Technical Note #5: IR Pulse Detector

- Sensor Output: Infrared pulse generator
- Sensor Installation and Maintenance: One person, one hour maximum; normal maintenance.
- Measurement Procedures: Install on face of utility meter with acrylic adhesive. Modulated infrared detector senses black rotation mark on meter. Does not require utility personnel for installation unless meter face must be removed to install rotation mark. Requires utility permission since sensor will typically be installed on utility meter.
- Instrument System Error: 2%.
- Comments: Easy to install with utility permission.

Technical Note #6: Shunted CTs on Secondaries

- Sensor Output: 333 mV full-scale analog output.
- Sensor Installation and Maintenance: One hour each for electrician and instrumentation technician; normal maintenance.
- Measurement Procedures: Shunted 5 amp split-core CTs are installed on existing meter CT secondaries. Installation may involve working "hot" inside large electrical distribution equipment.
- Instrument System Error: 2% to 3%.
- Comments: This is a relatively low-cost approach if a Type 4 DAS is available.

Technical Note #7: Whole Building or Service, New Meter—Shunted CTs

- Sensor Output: 333 mV analog output
- Sensor Installation and Maintenance: One hour each for instrumentation technician and electrician; normal maintenance.
- Measurement Procedures: Split core, shunted CTs are installed on service entrance and connected to DAS Type 5.
- Instrument System Error: 2%.
- Comments: Requires electrical service shutdown, coordination with facility, battery-powered lights in work area, etc.

Technical Note #8: Portable Recording Watt Meter

- Sensor Output: Analog output to dedicated DAS.
- Sensor Installation and Maintenance: One-half hour for instrumentation technician, mainly for measurement setup; normal maintenance.
- Measurement Procedures: This approach involves attaching "clamp-on" CTs and potential leads to a Dranatz or BMI type meter with data acquisition capability. The meter is connected to a load and operated for a specified period of time.
- Instrument System Error: 1% to 2%.
- Comments: This is a common diagnostic metering approach.
- Portable recording watt meter data must be combined with measurements of operating hours (see notes 9 and 10) to compute electricity use.

Technical Note #9: Portable Cumulative Run-Time Meter

- Sensor Output: Visual reading of digital display
- Sensor Installation and Maintenance: One-half hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Portable status indicator, e.g., photocell, or current indicator, is connected to a dedicated data logger, installed on the device to be monitored. Electrician not required.
- Instrument System Error: 2% to 5%.
- Comments: Easy to install and remove; easy to lose or steal.
- Run-time meter data must be combined with measurements of power (see notes 3 and 8) to compute electricity use.

Technical Note #10: Portable Time-of-Use Run-Time Meter

- Sensor Output: Analog (status) signal to DAS.
- Sensor Installation and Maintenance: One-half hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Status sensing device, e.g., photocell or CT, is attached to a dedicated data logger that generates and stores date and time stamped data, which is installed on the device to be monitored. Electrician not required. Portable computer can be used to retrieve data.
- Instrument System Error: 2% to 5%.
- Comments: Easy to install and remove; each to lose or steal.
- Run-time meter data must be combined with measurements of power (see notes 3 and 8) to compute electricity use.

Technical Note #11: Component, Device, or Appliance—Shunted CTs

- Sensor Output: 333 mV full-scale analog output.
- Sensor Installation and Maintenance: One hour each for instrumentation technician and electrician; normal maintenance.

- Measurement Procedures: Shunted CTs are installed at the device or at appropriate switch gear and connected to data logger.
- Instrument System Error: 2%.
- Comments: The use of split core CTs can often avert an electrical shutdown. High quality nickel core CTs should be used when monitoring variable frequency devices or other applications that produce a high harmonic content.

Technical Note #12: Pulse Splitter

- Sensor Output: An electronic device (pulse splitter) is installed on existing pulse-initiating kWh meter, which replicates pulse signal.
- Sensor Installation and Maintenance: Included in sensor cost since installation is typically conducted by utility meter shop personnel. Requires up to four hours for one person; zero maintenance.
- Instrument System Error: 1%.
- Measurement Procedures: A pulse splitter is typically installed on an existing revenue meter. The retrofit is not complex.
- Comments: Installation requires utility participation.

Technical Note #13: CTs on Secondaries and Watt Transducer

- Sensor Output: Analog output from CTs to watt transducer. Pulse or analog output from watt transducer to DAS.
- Sensor Installation and Maintenance: Two to four hours each for instrument technician and electrician; normal maintenance.
- Measurement Procedures: This approach involves installing CTs on the 5 amp secondaries of an existing meter. It may involve working "hot" inside large electrical distribution equipment. The new CTs are connected to a watt transducer, which also requires line reference voltage.
- Instrument System Error: 2% to 3%.
- Comments: Pulse splitter may be a better option if it is available.

Technical Note #14: Pulse Meter

- Sensor Installation and Maintenance: Installation is typically provided by utility or facility as part of the meter cost.
- Measurement Procedures: Typically installed by utility or facility personnel.
- Instrument System Error: 1%.
- Comments: Requires scheduling and coordination with utility and/or facility.

Technical Note #15: Whole Building or Service, New Meter—CTs and Watt Transducer

- Sensor Output: Watt transducer output can be analog or pulse.
- Sensor Installation and Maintenance: Two to four hours each for instrumentation technician and electrician; normal maintenance.
- Measurement Procedures: Split core CTs are installed on service entrance and connected to watt transducer. Watt transducer requires line reference voltage input.
- Instrument System Error: 2% to 3%.
- Comments: Requires electrical service shutdown, coordination with facility, battery lighting for work area, etc.

Technical Note #16: Component, Device, or Appliance—CTs and Watt Transducer

- Sensor Output: Pulse or analog output
- Sensor Installation and Maintenance: Two to four hours for instrumentation technician and electrician; normal maintenance.
- Measurement Procedures: Requires installation of CTs and connection of CTs and potential leads to a watt transducer. Use of split core CTs can often avoid electrical shutdown.
- Instrument System Error: 2% to 3%.
- Comments: Coordination with facility required for device shutdown.

A5.6.2.2 Gas Usage

Technical Note #17: Existing Energy Meter

- Sensor Output: Dial register.
- Sensor Installation and Maintenance: one-half hour for instrumentation technician; normal maintenance.
- Measurement Procedures: This approach involves reading an existing utility billing meter.
- Instrument System Error: 1%.

Technical Note #18: Combustion Efficiency

- Sensor Output: Digital display.
- Sensor Installation and Maintenance: One hour for instrumentation technician.
- Measurement Procedures: Probe inserted into combustion exhaust flue and measurements obtained. Approach may require drilling sampling port if one is not available.
- Instrument System Error: 2%.
- Comments: Commonly overlooked performance evaluation technique.

Technical Note #19: Pulse Initiator

- Sensor Installation and Maintenance: Labor costs included above; high maintenance.
- Measurement Procedures: A pulse head is normally installed on an existing meter by utility personnel. A meter changeout may be required.
- Instrument System Error: 2% to 3%.
- Comments: Sensor can be misaligned on installation, resulting in spurious data. Pulse output should be verified against dial meter reading.

Technical Note #20: New Pulse Meter

- Sensor Installation and Maintenance: Labor costs are included; high maintenance.
- Measurement Procedures: A new pulse-initiating natural gas meter is installed on the gas line feeding the load to be monitored.
- Instrument System Error: 2% to 3%.
- Comments: Meter installation is normally accomplished by utility personnel. Substantial plumbing is often required and local codes must be followed.

Technical Note #21: Run-Time Sensor

- Sensor Installation and Maintenance: One hour each for field technician and electrician; normal maintenance.
- Measurement Procedures: A run-time status is used to identify when a particular device is operating. The sensor is a simple contact closure that is wired into the device control circuitry and opens or closes depending on the operating status of the device.
- Instrument System Error: 1%.
- Comments: A status sensor and a one-time burner heat output measurement can be used as a proxy for use on natural gas-fueled appliances with constant output while operating (furnaces, etc.).

A5.6.2.3 Temperature

Technical Note #22: Ambient Indoor—Portable Electronic Thermometer

- Sensor Output: Visual reading on digital display.
- Sensor Installation and Maintenance: Fifteen minutes for an instrumentation technician maximum; normal maintenance.
- Measurement Procedures: A hand-held digital thermometer is used to record interior temperatures at specified locations.
- Instrument System Error: 2%.
- Comments: Care must be taken to select representative locations for temperature measurement. Substantial spatial variation in indoor temperature often exists.

Technical Note #23: Ambient Outdoor—Portable Electronic Thermometer

- Sensor Output: Visual reading on digital display.
- Sensor Installation and Maintenance: Fifteen minutes for instrumentation technician; normal maintenance.
- Measurement Procedures: A portable electronic thermometer is used to obtain a representative outdoor temperature reading.
- Instrument System Error: 2%.
- Comments: Be aware of outdoor "heat island" effects. Take care not to obtain readings near furnace flues or exhaust air outlets.

Technical Note #24: Domestic Water—Portable Electronic Thermometer

- Sensor Output: Visual reading of digital display.
- Sensor Installation and Maintenance: Fifteen minutes for instrumentation technician; normal maintenance.
- Measurement Procedures: An immersible temperature probe is placed in the water to be measured. Typically used to measure tap or shower water temperature.
- Instrument System Error: 2%.
- Comments: A simple measurement that is commonly undertaken.

Technical Note #25: Air in Ducts—Portable Electronic Thermometer

- Sensor Installation and Maintenance: One hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Temperature probe inserted in duct.
- Instrument System Error: 5%.
- Comments: Requires sampling port for inserting probe into duct. Port must be properly sealed after use.

Technical Note #26: Ambient Indoor—Portable Recording Electronic Thermometer

- Sensor Output: Analog signal to DAS.
- Sensor Cost: Multiple-channel systems are available.
- Sensor Installation and Maintenance: One hour for instrumentation technician; normal maintenance.
- Measurement Procedures: A temperature sensor(s) provides analog output to dedicated DAS. RTDs, thermistors, and thermocouples are all commonly used as sensors.
- Instrument System Error: 2%.
- Comments: A simple and easy to use approach when only temperature data are required.

Technical Note #27: Ambient Indoor—Electronic Temperature Sensor

- Sensor Output: Analog signal; output can be conditioned to meet DAS requirements.
- Sensor Cost: Depending on sensor and signal conditioning requirements
- Sensor Installation and Maintenance: One hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Sensor is mounted in an enclosure on an interior wall, typically 4-5 feet above floor level. Signal wire is routed back to the DAS. "Fishing" signal wire through ceilings and walls is often required.
- Instrument System Error: 1% to 2%.
- Comments: Sensor selection is a function of both accuracy requirements and DAS compatibility. A broad range of temperature sensor types is available.

Technical Note #28: Ambient Outdoor—Portable Recording Electronic Thermometer

- Sensor Output: Analog signal to dedicated DAS.
- Sensor Cost: Multiple-channel systems are available.

- Sensor Installation and Maintenance: One hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Sensor is installed in a “weathertite” enclosure in appropriate location. Signal wire is routed to the DAS.
- Instrument System Error: 2%.
- Comments: Choosing a representative exterior temperature sensor location can be challenging. The sensor must not be exposed to direct sunlight at any time.

Technical Note #29: Electronic Temperature Sensor

- Sensor Output: Analog signal to DAS, conditioned as required.
- Sensor Installation and Maintenance: one hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Temperature sensor is installed in a “weathertite” enclosure in an appropriate location. Signal wire is routed to DAS.
- Instrument System Error: 1% to 2%.
- Comments: Outdoor temperature sensor location can be critical. It must be representative.

Technical Note #30: Domestic Water—Surface-Mounted Electronic Temperature Sensor

- Sensor Output: Analog signal; conditioned as required.
- Sensor Installation and Maintenance: Two hours for instrumentation technician; normal maintenance.
- Measurement Procedures: Temperature sensor is cemented to outside surface of metal pipe. Signal wire is routed to DAS.
- Instrument System Error: 2%.
- Comments: Thermal contact between temperature sensor and pipe is critical.

Technical Note #31: Domestic Water—Electronic Temperature Sensor and Thermowell

- Sensor Output: Analog signal to DAS; conditioned as required.
- Sensor Installation and Maintenance: One hour for instrumentation specialist; one hour for plumber; normal maintenance.
- Measurement Procedures: Thermowell is installed in plumbing system; temperature sensor is installed in thermowell; signal wire is routed to DAS.
- Instrument System Error: 1% to 2%.
- Comments: Licensed plumber typically required for sensor installation.

Technical Note #32: HVAC Water in Pipe—Surface-Mounted Electronic Temperature Sensor

- Sensor Output: Analog signal; conditioned as required.
- Sensor Installation and Maintenance: One to two hours for instrumentation technician; normal maintenance.
- Measurement Procedures: Sensor is mounted on metallic exterior surface of pipe. Signal cable routed to DAS. Pipe insulation must be removed as necessary.
- Instrument System Error: 2% to 5%.
- Comments: Measurement technique may not be satisfactory for large diameter pipes.

Technical Note #33: Refrigerant in Pipe—Surface-Mounted Electronic Temperature Sensor

- Sensor Installation and Maintenance: One to two hours for instrumentation technician; normal maintenance.
- Measurement Procedures: Sensor is mounted on exterior surface of refrigerant pipe.
- Instrument System Error: 2% to 5%.
- Comments: Installation similar to HVAC fluid in pipe application

Technical Note #34: Electronic Temperature Sensor Array

- Sensor Installation and Maintenance: Two to four hours for instrumentation technician; normal maintenance.
- Measurement Procedures: Temperature sensor array installed in duct.
- Instrument System Error: 2% to 5%.
- Comments: Multiple sensors are averaged to produce mean air temperature. Installation can be complex.

Technical Note #35: HVAC Water in Pipe—Electronic Temperature Sensor and Thermowell

- Sensor Output: Analog signal; conditioned as required.
- Sensor Cost: Includes thermowell and hot tap costs.
- Sensor Installation and Maintenance: Two hours for instrumentation technician; normal maintenance.
- Measurement Procedures: Pipe is hot-tapped and temperature sensor inserted. Signal cable routed to DAS.
- Instrument System Error: 1%.
- Comments: Stringent safety requirements required for hot-tapping. Certified welder required.

Technical Note #36: Refrigerant in Pipe—Electronic Temperature Sensor and Thermowell

- Sensor installation and Maintenance: Four hours for instrumentation technician; normal maintenance.
- Measurement Procedures: Thermowell is installed in refrigerant line; temperature sensor installed in thermowell.
- Instrument System Error: 2% to 5%.
- Comments: Refrigerant leaks must be scrupulously avoided. Cost of installing thermowell included in sensor cost.

A5.6.2.4 Relative Humidity

Technical Note #37: Ambient Indoor—Sling Psychrometer

- Sensor Output: Visual reading of thermometers
- Sensor Installation and Maintenance: Fifteen minutes for instrumentation technician; normal maintenance.
- Measurement Procedures: Sling psychrometer is rotated

and visual reading of wet- and dry-bulb temperatures is obtained.

- Instrument System Error: 2%.
- Comments: Still in common use for "one-time" measurements.

Technical Note #38: Ambient Indoor—Portable Electronic RH Meter

- Sensor Output: Visual reading of digital display
- Sensor Installation and Maintenance: Fifteen minutes for instrumentation technician; normal maintenance.
- Measurement Procedures: Read hand-held instrument.
- Instrument System Error: 2% to 5%.
- Comments: Instrumentation cost depends on accuracy requirements.

Technical Note #39: Ambient Outdoor—Sling Psychrometer

- Sensor Output: Visual reading of thermometers
- Sensor Installation and Maintenance: Fifteen minutes for instrumentation technician; normal maintenance.
- Measurement Procedures: Sling psychrometer is rotated and visual reading of wet- and dry-bulb temperatures is obtained.
- Instrument System Error: 2%.
- Comments: Still in common use for "one-time" measurements. Can be used both indoors and outdoors. Not accurate above 80% relative humidity. Avoid operating in direct sunlight.

Technical Note #40: Ambient Outdoor—Portable Electronic RH Meter

- Sensor Output: Visual reading of digital display
- Sensor Installation and Maintenance: Fifteen minutes for instrumentation technician; normal maintenance.
- Measurement Procedures: Read hand-held instrument.
- Instrument System Error: 2% to 5%.
- Comments: Instrumentation cost depends on accuracy requirements. Usable both indoors and outdoors.

Technical Note #41: Ambient Indoor—Electronic RH Sensor

- Sensor Output: Analog signal; conditioned as appropriate.
- Sensor Installation and Maintenance: One to two hours for instrumentation technician; one hour for electrician may be required for installation of sensor power supply.
- Measurement Procedures: Sensor typically installed on interior wall, often in association with temperature sensor.
- Instrument System Error: 2% to 5%.
- Comments: Sensors typically require separate low-voltage power supply for operation.

Technical Note #42: Ambient Outdoor—Electronic RH Sensor

- Sensor Output: Analog signal; conditioned as appropriate.
- Sensor Installation and Maintenance: One to two hours for instrumentation technician; one hour for electrician may be required for installation of sensor power supply.
- Measurement Procedures: Sensor must be "weathertite." Typically installed in weather station or other enclosure that includes a solar shield.
- Instrument System Error: 2% to 5%.
- Comments: Sensors typically require separate low-voltage power supply for operation. Electronics cannot operate in a condensing environment.

Technical Note #43: Electronic Dew Point Sensor

- Sensor Output: Analog output; conditioned as appropriate.
- Sensor Installation and Maintenance: Two to four hours for instrumentation technician; maintenance cost $660; requires monthly maintenance.
- Instrument System Error: 2%.
- Comments: Requires meteorological enclosure.

A5.6.2.5 Flow Rate

Technical Note #44: Domestic Water—Bucket/Stopwatch

- Sensor Output: Analog with signal conditioning as necessary.
- Sensor Installation and Maintenance: One-half hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Time required to fill a fixed volume container is measured.
- Instrument System Error: 5%.
- Comments: A calibrated "microweir" can be used to increase accuracy.

Technical Note #45: Domestic Hot Water—Bucket/Stopwatch

- Sensor Installation and Maintenance: One-half hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Time required to fill a fixed volume container is measured.
- Instrument System Error: 5%.
- Comments: A calibrated "microweir" can be used to increase accuracy. See *Home Energy* July-Aug. 1991.

Technical Note #46: HVAC Hydronic Fluids—Portable Ultrasonic Flow Meter

- Sensor Output: Visual reading of digital display
- Sensor Installation and Maintenance: One hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Meter sensor is adjustable to fit a variety of pipe diameters.
- Instrument System Error: 5%.
- Comments: Proper application and installation are critical. Potentially useful for in-field sensor verification.

Technical Note #47: Refrigerant Liquid—Portable Ultrasonic Flow Meter

- Sensor Installation and Maintenance: One hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Hand-held instrument measures through pipe and insulation.
- Instrument System Error: 5%.
- Comments: This non-intrusive measurement approach may be particularly appropriate for refrigerant measurement where intrusive flow measurements are both costly and difficult to retrofit.

Technical Note #48: Portable Flow Measurement Probe

- Sensor Installation and Maintenance: One hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Flow measurement probe inserted through sampling port into duct.
- Instrument System Error: 5%.
- Comments: Requires a measurement sampling port for inserting probe into duct. Port must be properly sealed after use.

Technical Note #49: Flow Hood

- Sensor Installation and Maintenance: One-half hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Flow hood placed over register or grille to be measured.
- Instrument System Error: 2% to 5%.
- Comments: Flow hoods are used to measure air flow through supply and return air registers and grilles.

Technical Note #50: Pressurization/Depressurization Test

- Sensor Installation and Maintenance: One hour for instrumentation technician; normal maintenance.
- Measurement Procedures: Measurement system connected to single register; other registers in duct system sealed.
- Instrument System Error: 3% to 5%.
- Comments: Measurement system consists primarily of a variable speed fan that can be connected directly to a duct system to pressurize or depressurize a forced air distribution system. Very accurate measurements of duct leakage can be obtained with careful measurement.

Technical Note #51: Portable Flow Meter

- Sensor Output: Accumulating register
- Sensor Installation and Maintenance: One-half hour for instrumentation technician.
- Measurement Procedures: Flow meter is installed on existing screw-on shower head or faucet fixture.
- Instrument System Error: 4%.
- Comments:

Technical Note #52: Domestic Water—Accumulating Flow Meter

- Sensor Output: Visual reading of accumulating register.
- Sensor Installation and Maintenance: One hour each for plumber and instrumentation technician.
- Measurement Procedures: Utility grade accumulating water meter installed on water line to be measured.
- Instrument System Error: 1% to 2%.
- Comments: Requires licensed plumber for installation.

Technical Note #53: Pulse Flow Meter

- Sensor Installation and Maintenance: One hour for plumber, one hour for instrumentation technician; normal maintenance.
- Measurement Procedures: A utility grade pulse-initiating water meter is installed in the water line to be measured. Signal wire is routed to the DAS.
- Instrument System Error: 2%.
- Comments: A licensed plumber will typically be required for installation.

Technical Note #54: Domestic Hot Water—Accumulating Flow Meter

- Sensor Output: Visual reading of accumulating register.
- Sensor Installation and Maintenance: One hour each for plumber and instrumentation technician.
- Measurement Procedures: Hot water rated accumulating water meter installed on water line to be measured.
- Instrument System Error: 1% to 2%.
- Comments: Requires licensed plumber for installation.

Technical Note #55: Pulse Flow Meter

- Sensor Installation and Maintenance: One hour for plumber, one hour for instrumentation technician; normal maintenance.
- Measurement Procedures: A high temperature rated, pulse-initiating water meter is installed in the water line to be measured. Signal wire is routed to the DAS.
- Instrument System Error: 2%.
- Comments: A licensed plumber will typically be required for installation.

Technical Note #56: HVAC Hydronic Fluids—In-Line or Insertion Flow Meter

- Sensor Output: Pulse or analog.
- Sensor Cost: Includes weldolet and hot-tap costs.
- Sensor Installation and Maintenance: Four hours for instrumentation specialist; high maintenance.
- Measurement Procedures: Flow meter inserted into pipe through weldolet. Signal cable routed to DAS.
- Instrument System Error: 2%.
- Comments: Various flow meter types are available. Routine recalibration is important.

Technical Note #57: Refrigerant Liquid—In-Line or Insertion Flow Meter

- Sensor Output: digital (pulse) signal.
- Sensor Installation and Maintenance: Four to six hours for instrumentation technician; high maintenance.
- Measurement Procedures: Flow meter is installed in refrigerant line.
- Instrument System Error: 2%.
- Comments: Refrigerant leaks must be scrupulously avoided. Cost of installing hot tap and weldolet included in sensor cost. Routine recalibration is important.

Technical Note #58: Air in Ducts—Flow Measurement Array

- Sensor Output: Analog signal of average flow rate.
- Sensor Installation and Maintenance: Four to six hours for instrumentation technician; high maintenance.
- Measurement Procedures: Flow measurement array installed in air duct.
- Instrument System Error: 2% to 5%.
- Comments: Measurement systems using pitot arrays, mass flow meters, or thermal anemometers are available. Measurements are temperature sensitive.

Technical Note #59: Refrigerant Vapor—Flow Measurement Array

- Sensor Output: Analog signal of average flow rate.
- Sensor Installation and Maintenance: Four to six hours for instrumentation technician; high maintenance.
- Measurement Procedures: Flow measurement probe installed in refrigerant line.
- Instrument System Error: 2% to 5%.
- Comments: Refrigerant leaks must be scrupulously avoided. Retrofit sensor installation can be complex and must be addressed on a site specific basis.

A5.6.2.6 Hydronic Btu Metering

Technical Note #60: Electronic Btu Meter

- Sensor Installation and Maintenance: Two hours for instrumentation technician; high maintenance.
- Measurement Procedures: Temperature and flow sensor outputs connected to Btu meter. Signal cable routed from Btu meter to DAS.
- Instrument System Error: 2% to 5%.
- Comments: Accuracy depends on accuracy of input sensors. Btu meters are available at a wide range of costs. Note that the Btu meter price quoted here does not include sensors or sensor installation.

Technical Note #61: Data Logger—Real-Time Math

- Sensor Installation and Maintenance: Two to four hours for instrumentation technician, time to program data logger; normal maintenance.
- Measurement Procedures: Conditional data logging capability (real-time mathematics) is used to calculate BTUs from temperature and flow data.
- Instrument System Error: 2% to 5%.
- Comments: Accuracy depends on input sensor accuracy. Real-time mathematics capability is not available on all DAS.

A5.6.2.7 Nonmechanical Ventilation

Technical Note #62: SF_6

- Sensor Installation and Maintenance: Three hours for instrumentation technician; zero maintenance.
- Measurement Procedures: Technician initiates the dispersion of SF_6 gas, then collects periodic air samples over a two-hour period. Gas chromatograph or infrared spectrometer required for analysis.
- Instrument System Error: 5%.
- Comments: Substantial training is required to properly conduct test. Measurement produces total ventilation rate. Nonmechanical ventilation is computed by subtracting mechanical ventilation from this total. See electricity use measurement type for mechanical ventilation measurement protocols.

Technical Note #63: PFT

- Sensor Cost: Test (four zones) including analysis.
- Sensor Installation and Maintenance: Two hours for instrumentation technician; one hour for deployment; one hour for retrieval; zero maintenance.
- Measurement Procedures: PFT sources and samplers are deployed in building per protocol.
- Instrument System Error: 5% to 10%.
- Comments: PFT test is temperature dependent. Measurement produces "average" ventilation rate. Nonmechanical ventilation is computed by subtracting mechanical ventilation from this total. See electricity use measurement type for mechanical ventilation measurement protocols.

Technical Note #64: Blower Door

- Sensor Output: Visual reading of digital gauges; computer printout.
- Sensor Installation and Maintenance: Two hours for instrumentation technician; normal maintenance.
- Measurement Procedures: Blower door test protocol is followed. Computer-controlled fan with digital micromanometer pressurizes/depressurizes the building.
- Instrument System Error: 5%.
- Comments: Trained technician required for measurement. Measurement produces estimated ventilation rate. Nonmechanical ventilation is computed by subtracting mechanical ventilation from this total. See electricity use measurement type for mechanical ventilation measurement protocols.

A5.6.2.8 Pressure

Technical Note #65: Air in Ducts—Pressure Transmitter

- Sensor Output: Analog signal
- Sensor Installation and Maintenance: Two to four hours for instrumentation technician; normal maintenance.
- Measurement Procedures: Pressure transmitter installed in air duct.
- Instrument System Error: 1% to 5%.
- Comments: Installation costs and requirements will vary with specific sites

Technical Note #66: Refrigerant Vapor—Pressure Transmitter

- Sensor Output: Analog signal.
- Sensor Installation and Maintenance: Two to four hours for instrumentation technician; normal maintenance
- Measurement Procedures: Pressure transmitter installed in refrigerant line.
- Instrument System Error: 1% to 5%.
- Comments: Instrumentation must be compatible with refrigerant working fluid. Installation requirements are very site specific. Refrigerant leaks must be scrupulously avoided.

Technical Note #67: Pressure Transducer

- Sensor Output: Analog signal.
- Sensor Installation and Maintenance: Two to four hours for instrumentation technician; normal maintenance.
- Measurement Procedures: Pressure transducer installed in pipe.
- Instrument System Error: 1% to 5%.
- Comments: Installation in retrofit applications may be complex.

A5.6.2.9 Solar Radiation

Technical Note #68: Pyrheliometer

- Sensor Output: Analog with signal conditioning as necessary.
- Sensor Installation and Maintenance: Four hours for instrumentation technician; normal maintenance.
- Measurement Procedures: Pyrheliometer is mounted on a flat surface that has direct unshaded solar exposure during all hours of the year. Tracker is operated by a computer-controlled motor. Signal cable is routed from unit to DAS.
- Instrument System Error: 1% to 5%.
- Comments: Expensive instrumentation typically used for research purposes.

Technical Note #69: Pyranometer

- Sensor Output: Analog signal, conditioned as required.
- Sensor Installation and Maintenance: Two hours for instrumentation technician; high maintenance.
- Measurement Procedures: Pyranometers are typically mounted on an horizontal exterior surface. Signal cable is routed to the DAS.
- Instrument System Error: 2% to 5%.
- Comments: Horizontal solar radiation data can be converted, by algorithm, to incident radiation at any other surface angle. Multi-pyranometer array may be required for accurate measurements.

A5.6.2.10 Door Position

Technical Note #70: Contact Closure

- Sensor Output: Digital (pulse) signal.
- Sensor Installation and Maintenance: One to two hours for instrumentation technician: normal maintenance.
- Measurement Procedures: Sensor installed on door or window.
- Instrument System Error: 2%.
- Comments: System measures status (open or closed) only. Actual position (e.g., half open) cannot be determined.

A5.6.2.11 Production Rate. May be accomplished with many of the other methods described in the table. Applicable methods must be selected for each monitoring project.

A5.6.2.12 RPM

Technical Note #71: Portable Tachometer/Stroboscope

- Sensor Installation and Maintenance: One-half hour for instrumentation technician.
- Measurement Procedures: Hand-held instrument used on device or appliance.
- Instrument System Error: 1%.
- Comments: Both contact or non-contact models are available.

Technical Note #72: Electronic RPM Sensor

- Sensor Output: Analog signal.
- Sensor Installation and Maintenance: Two to four hours for instrumentation technician; normal maintenance.
- Measurement Procedures: Sensor installed in contact with or aligned with device or appliance to be measured.
- Instrument System Error: 1%.
- Comments: Proximity, optical and magnetic sensors available. Output can be conditioned as required for data acquisition system.

A5.6.2.13 On-Time

Technical Note #73: Status Sensor

- Sensor Output: Digital output.
- Sensor Installation and Maintenance: One hour each for electrician and instrumentation technician; normal maintenance.
- Measurement Procedures: Status sensor is installed on control circuitry of device being monitored. Sensor is opened or closed depending on operating status of device.
- Instrument System Error: 2%.
- Comments: Often required for evaluating the performance of devices with multiple operating conditions, such as heat pumps and refrigeration systems.

A5.6.2.14 Wind Speed

Technical Note #74: Hand-Held Anemometer

- Sensor Output: Visual reading.
- Sensor Installation and Maintenance: Fifteen minutes for instrumentation technician; normal maintenance.
- Measurement Procedures: Instrumentation technician obtains reading.
- Instrument System Error: 10%.
- Comments: Identifying a representative measurement is crucial. Microclimatic variation in wind speed can be very significant.

Technical Note #75: Recording Anemometer

- Sensor Output: Analog signal, conditioned as required.
- Sensor Installation and Maintenance: Two to four hours for instrumentation technician; high maintenance.
- Measurement Procedures: Cup anemometer is installed on mast in representative location. Signal cable is routed to DAS.
- Instrument System Error: 5%.
- Comments: Measurement error increases at low wind speeds. Wind speeds below 5-7 mph are often not recorded.

Technical Note #76: Meteorological Grade Recording Anemometer

- Sensor Output: Analog signal; conditioned as required.
- Sensor Installation and Maintenance: Four - eight hours for instrumentation technician; high maintenance.
- Measurement Procedures: Cup anemometer is mounted on mast in representative location. Signal cable routed to DAS.
- Instrument System Error: 2%.
- Comments: This level of accuracy is often not required in building measurement experiments.

A5.7 Sensor Type Definitions. This clause includes an alphabetical listing of definitions for each of the sensor types that are cited in the Table of Site Specific Measurement Methods in A5.6.1. Note they may not be consistent with those provided elsewhere in this guideline.

accumulating flow meter: a standard utility-grade water meter that records accumulated flow.

blower door: a large, accurately controllable fan installed in a doorway, used to pressurize and depressurize a building. Blower door test results are used to estimate building envelope tightness and to infer an infiltration rate.

bucket/stopwatch: a measurement system consisting of a bucket and a stopwatch, which is used to measure water flow rate. The time required to fill a fixed volume bucket is measured.

combustion efficiency test equipment: monitoring equipment inserted into the flue of a combustion appliance, which monitor the concentration of various combustion byproducts and ultimately provide a measurement of combustion efficiency.

contact closure: this sensor is simply a switch, which breaks or closes an electric circuit depending on whether a door, window, or other system is open or closed.

CTs and watt transducer: a measurement approach involving the installation of current transformers on the wires at the electrical service entrance or, alternatively, on the wires serving a component, device, or appliance. The CT leads are connected to a watt transducer, which provides a digital or analog output to the data acquisition system.

CTs on secondaries and watt transducer: a measurement approach in which current transformers are placed on the secondary side of existing current transformers connected to an existing energy meter. The secondaries from these new CTs are connected to a watt transducer. The output of the watt transducer is proportional to the output of the existing energy meter.

data logger, real-time math: some data acquisition systems have the ability to do real-time mathematical calculations. These systems can accept flow and temperature inputs and calculate BTUs without an external BTU meter.

demand meter: an electric meter that records peak demand as well as energy.

duct pressurization test equipment: a specialized fan and other equipment that is used to pressurize ducts and thus measure duct air leakage.

electronic BTU meter: a microprocessor-based system, which receives flow and temperature sensor inputs and determines a heat transfer rate. BTU meters often generate a pulse (digital) output that is proportional to BTUs

electronic dew-point sensor: an electronic dew-point sensor commonly uses a chilled mirror system to determine the dew-point temperature. Such sensors typically require nearly constant maintenance and routine calibration.

electronic RH sensor: both resistance and capacitance type sensors are in use. One common sensor uses a bulk polymer, which changes in capacitance with changes in absorbed moisture. This capacitance change is then translated into a changing output signal proportional to relative humidity.

electronic RPM sensor: this sensor involves a tachometer system with an analog signal output, conditioned as required for data acquisition purposes. Optical, magnetic, and proximity sensors are available.

electronic temperature sensor: an electronic device (thermocouple, thermistor, resistance temperature device [RTD], integrated circuit) that provides an output proportional to temperature. Common integrated circuit temperature sensors include LM34, AD590, and AD592.

electronic temperature sensor and thermowell: a measurement system consisting of an electronic temperature sensor and the thermowell into which it is inserted. This system is used to measure the temperature of a fluid flowing in a pipe.

existing energy meter (electricity): the electric utility billing meter that currently exists at the building or service. Occasionally, non-revenue electric meters may be present, particularly in large facilities.

existing energy meter (natural gas): the natural gas utility billing meter that currently exists at the building or service.

flow hood: a large funnel-shaped device that is placed over grilles, vents, or registers to measure air flow rates.

flow measurement array: a group of sensors installed in a duct or pipe, designed to measure air or refrigerant vapor flow rates. Pitot tubes are commonly used in such arrays.

hand-held anemometer: a hand-held device for estimating wind speed. The accuracy of such spot measurement devices is limited.

infrared (IR) pulse detector: a device cemented to the transparent billing meter cover, which senses the black mark on the spinning billing meter rotor as it passes a fixed point. The sensor output is an electronic pulse (digital signal) proportional to kWh use.

in-line or insertion flow meter: devices for measuring fluid flow rate. Many varieties of these devices are available. Most have specific applications, advantages, and disadvantages. All require plumbers and/or welders for installation.

meteorological grade recording anemometer: meteorological grade recording anemometers are carefully designed to rotate at low wind speeds and provide high levels of accuracy.

PFT: the perfluorocarbon tracer (PFT) gas test measures a building's "average" ventilation rate over a fixed period of time (typically one month). The PFT gas disperses at a constant rate from a source and is absorbed by a sampler. The amount of PFT absorbed by the sampler is proportional to a building's average ventilation rate over that time period.

portable cumulative run-time meter: a small microprocessor with an attached sensor that records "run-time" of a device or appliance. Typical sensors include photocells (lighting loggers), inductive devices (motor loggers), or CTs.

portable electronic RH meter: a hand-held device consisting of an electronic sensor and a digital display, which provides spot relative humidity measurements.

portable electronic thermometer: a hand-held temperature measurement device consisting of a sensor (commonly a thermocouple) and digital output device that displays temperature. Sensors are available for various spot temperature measurement applications.

portable flow measurement probe: a hand-held instrument with a probe that is inserted through a port into a duct or held in the ambient air and provides a digital output display of flow rate.

portable flow meter: a portable flowmeter that screws onto a shower head, faucet, or other plumbing outlet. Output is accumulated flow from the plumbing outlet to which the shower head is attached.

portable recording watt meter: an electrical measurement device with built-in power-recording capability. This device can measure power factor and harmonics as well as true power and kVA.

portable tachometer/ stroboscope: a hand-held device used to measure motor revolutions (RPM). Both contact and noncontact models are available.

portable time-of-use run-time meter: a variation of the "run-time" meter, which provides a time and date stamp whenever a device turns on or off. The same input sensors are available.

portable watt meter: a hand-held meter that accepts inputs from current (CTs) and potential (spring clips attached to a voltage source) leads and provides an output of true power on a digital display.

portable recording electronic thermometer: an electronic temperature measurement device consisting of one or more temperature sensors and a dedicated data acquisition system. Stored data are commonly downloaded to a portable computer using an RS 232 type connection.

portable ultrasonic flow meter: a hand-held device that uses ultrasonic frequency radiation to measure liquid flow rates in pipes. This is a non-intrusive measurement device, a substantial advantage for short-term measurements.

pressure transducer: a device that converts the output of a pressure sensor to an output (0-5 V, 4-20 mA, etc.) that can be interpreted by a data acquisition system. Pressure transducers can be used in liquid or gaseous media.

pressure transmitter: a sensor designed to be inserted into a duct or pipe to measure air or refrigerant vapor pressure.

pulse flow meter: a standard, utility-grade flow meter with a pulse initiator attached, which provides a pulse (digital) output proportional to flow rate.

pulse initiator: also known as a pulse head. A device, normally activated by the gearing of an electromechanical meter, which converts energy use to pulses that can be recorded on magnetic tape or by a solid-state recorder. The number of pulses per time period is proportional to the quantity being metered. Also refers to a device fitted onto a bellows type gas meter, which produces a pulse (digital) output proportional to gas flow.

pulse meter (pulse-initiating kWh meter): a utility-grade kWh meter with a pulse (digital) output proportional to power use. This type of meter has been commonly installed by utilities for load research purposes.

pulse meter (pulse-initiating natural gas meter): a utility-grade natural gas meter with a pulse (digital) output proportional to gas flow. These meters are commonly used in load research studies.

pulse splitter: an electronic device that splits the output from a pulse-initiating utility kWh meter so that the signal is replicated and can be used for billing purposes by a utility as well as independently for evaluation purposes by a monitoring contractor.

pyranometer: a simple sensor for measuring global solar radiation on a surface.

pyrheliometer: a tracking device for measuring direct solar radiation. The most sophisticated systems involve computerized control.

recording anemometer: typically consists of a rotating cup or cup and vane system on an elevated mast. The sensor generates an analog output (often an AC current) that can be conditioned to meet data acquisition system needs.

run-time sensor: also known as a status sensor. A relay, switch, current transformer, or other sensor wired into the control circuitry of a device or appliance, which changes status when the device is operating. A data acquisition system (DAS) is used to sense this change in status and convert the sensor output to "run-time."

SF_6 test: this test measures the instantaneous ventilation rate of a building. A fixed amount of sulfur hexafluoride tracer gas is dispersed in a building and its dispersion (dilution) rate is measured over time. This dilution rate is equivalent to the building ventilation rate.

shunted CTs: also called current transducers. A current transformer provides a current output proportional to the current in the primary wire being measured. A shunt resistor can be applied across the CT leads transducing the secondary current output into a voltage. A common output voltage from a shunted CT is 333 mV full scale. The shunted CTs are connected directly to a data acquisition system with the capability to produce real-time power measurements.

shunted CTs on secondaries: in this metering approach, shunted CTs are placed on the secondary side of existing current transformers connected to an existing energy meter. The secondaries from these new CTs are connected directly to a Type 4 data acquisition system.

sling psychrometer: a wet- and a dry-bulb thermometer, mounted on a rotating shaft and whirled in the air to measure relative humidity. The device is useful for spot measurements only.

status sensor: also known as a run-time sensor. A relay, switch, current transformer, or other sensor wired into the control circuitry of a device or appliance, which changes status when the device is operating. A data acquisition system is used to sense this change in status and convert the sensor output to "run-time."

surface-mounted electronic temperature sensor: an electronic temperature sensor mounted on the exterior surface of a metal pipe and used to provide a proxy temperature measurement of a fluid flowing in the pipe.

(This informative annex is not part of ASHRAE Guideline 14 but is provided for informational purposes only.)

ANNEX B: DETERMINATION OF SAVINGS UNCERTAINTY

B1 Scope and Objective

Any decision to implement a particular energy conserving measure (ECM) is based on a financial risk evaluation in conjunction with a technical evaluation. People in positions of decision making are often not engineers but are typically building owners or businessmen. Hence, though they would rely on the engineers to provide a proper perspective of the various technical alternatives, they (or their financial advisors) would determine the financial implications and decide whether to go ahead or cancel the project. Thus, a key factor of a project is the financial risk analysis, which to engineers entails determining the uncertainty in the estimated or measured savings due to the ECM. Subsequently, a proper financial risk analysis would use the engineering uncertainty values in conjunction with other sources of uncertainty, such as year-to-year uncertainties in building operation, life of equipment, economic factors, interest and inflation rates, etc. A detailed treatment and perspective of engineering uncertainties versus economic uncertainties is provided by Kammerud et al., (1999).

The objective of this annex is to present some of the underlying concepts and the pertinent formulae for determining the uncertainty in the savings from an engineering point of view. As stated in clause 7.7 of ASHRAE Guideline 14, the uncertainty in savings can be attributed to errors in assumptions, sampling errors, measurement errors, and to prediction errors in the regression models. The scope of this annex is mainly limited to the last two sources only, with a pertinent discussion on sampling uncertainty.

B2 Brief Preamble of Uncertainty and Sources of Uncertainty

B2.1 Need for Uncertainty Analysis. Any measurement has some error (or deviation) associated with it. Such error is the difference between the measured value and the true value. A statement of measured value without an accompanying uncertainty statement has limited meaning. Uncertainty is the interval around the measured value within which the true value is expected to fall with some stated confidence. "Good data" does not describe data that yield the desired answer; it describes data that yield a result within the intended uncertainty interval. The certainty of the data taken will provide the degree of confidence to the answer provided. Dieck (1992) states, "Test results should never be reported without also reporting their measurement uncertainty. No manager or process owner should take action based on test results with an undefined measurement uncertainty." The uncertainty statement gives the party who will be using the measurement result a means to assess its value. It is especially important to perform an uncertainty analysis when making measurements that will have financial or contractual implications and that may end up being examined in court.

Measurements made in the field are especially subject to potential errors. In contrast to measurements made under the controlled conditions of a laboratory setting, field measurements are typically made under less predictable circumstances and with less accurate and less expensive instrumentation. Further, field measurements are vulnerable to errors arising from variable measurement conditions (the method employed may not be the best choice for all conditions), from limited instrument field calibration (typically more complex and expensive), from simplified data sampling and archiving methods employed, and from limitations in the ability to adjust instruments in the field.

With appropriate care, the conscientious measurement practitioner can minimize many of these sources of error. But what differentiates this practitioner's result from that of someone who does not consider sources of error or does little to minimize sources of error? The conscientious measurement practitioner has developed a procedure by which an uncertainty statement can be ascribed to the result and has also optimized the measurement system to provide maximum benefit for the least cost. The practitioner who does not consider sources of error probably has thus not maximized benefits.

B2.2 What is Uncertainty? Several practitioners use the terms *uncertainty* and *error* interchangeably. We shall, in this annex, adopt the view that one uses *error* when the "exact" value is known, while *uncertainty* is used when no such knowledge is available. Hence *uncertainty* is the more relevant term to use for specifying improper knowledge in the present context. The concept of prediction uncertainty can be better understood in terms of confidence limits. Confidence limits define the range of values that can be expected to include the true value with a stated probability (ASHRAE 1990). Thus, a statement that the 95% confidence limits are 5.1 to 8.2 implies that the true value will be contained between the interval bounded by 5.1 and 8.2 in 19 out of 20 predictions, or, more loosely, that we are 95% confident that the true value lies between 5.1 and 8.2. The uncertainty X of a quantity X can be related to the standard deviation (which is the square root of the variance). Thus, the "true" mean value of the random variable is bounded by

$$\bar{X} \pm \Delta X = \bar{X} \pm \frac{(t_{\alpha/2,\, n-1} \cdot \sigma)}{\sqrt{n}} \qquad \text{(B-1)}$$

where $t_{\alpha/2,\, n-1}$ is the t-statistic with probability or confidence level of $(1-\alpha/2)$ and (n-1) degrees of freedom (tabulated in most statistical textbooks), α is the significance level and σ^2 is the estimated variance. Note that some prefer to use the symbol ε for uncertainty instead of Δ used in this document. Statisticians also use SE to characterize variability or uncertainty.

B2.3 Confidence and Precision. Confidence and precision issues in the context of performance contracting are discussed by Goldberg (1996). The following is a condensation of that discussion.

Specification of the accuracy of an estimate requires not only the absolute or relative bounds (cost savings ±$20,000 or ±20%) but also the level of confidence that the true value is within those bounds. While this requirement can seem to be a fine point, a statistical precision statement without a confidence level defined is, in fact, meaningless. By allowing the confidence to be low enough, the precision bounds can be made arbitrarily tight.

For example, suppose the precision for a particular estimate is around ±10% at 80% confidence. Then (using the normal distribution, which is the basis for most precision calculations) the precision would be around ±5% at 50% confidence, or ±20% at 99% confidence. Providing the precision statement (±X) without the confidence level tells nothing. Likewise, comparing precision levels without knowing if they are reported at the same level of confidence is meaningless.

Statistical precision is not the only consideration in specifying monitoring requirements. However, it is useful for understand the meaning of statistical precision measures and the implications of different sampling strategies in terms of those measures.

B2.3.1 Precision Standards. The need for precision standards in M&V has been the subject of some debate. In the context of evaluation, a 90/10 standard, meaning 10% relative precision at 90% confidence, is often invoked. Another way of looking at this standard is that there is a 90% chance of being within 10% of the real value. This standard is included in California's Monitoring and Evaluation Protocols and is also the basis for the sampling requirements of various M&V protocols.

The requirement of 10% precision at 90% confidence has been adopted in part by the extension of the Public Utilities Regulatory Policy Act (PURPA) requirements for a class load research sample. Other precision standards are applied in other disciplines.

The extension of the 90/10 rule from load research to evaluation and verification has been made in several areas, but it raises some questions. One question is what parameters the criterion should be applied to. A second question is the level of disaggregation at which the criterion should be imposed. In the load research context, the parameter of interest may be the load at a given hour, and the level of disaggregation is the revenue class. In evaluation, monitoring, and verification, the parameter of ultimate interest may be the savings in load, energy, or energy costs at prevailing rates. The level of disaggregation may be critical in the context of M&V. This level reflects—or implicitly defines—the monitoring objectives and strongly affects the monitoring costs.

B2.4 Sources of Uncertainty. At the onset, during the analysis of measured data, we shall distinguish between uncertainty with and without sampling errors. The uncertainty due to sampling is discussed first.

B2.4.1 Sampling Uncertainty. Sampling error refers to errors resulting from the fact that a sample of units were observed rather than observing the entire set of units under study. This strategy is primarily adopted in order to reduce monitoring costs. The simplest sampling situation is that of a simple random sample. With this type of sample, a fixed number q of units is selected at random from a total population of Q units. Each unit has the same probability q/Q of being included in the sample. In this case, the standard deviation of the population is estimated as the standard deviation of the sample using Q-1 instead of Q. The standard error of the estimated mean (which is analogous to the root mean square error, RMSE) is given by

$$SE(y) = \sqrt{(1-q/Q)\left[\sum_{i=1}^{n}(y_i-\bar{y})^2/(q-1)\right]/q}. \qquad \text{(B-2)}$$

For more complicated random samples, more complex formulas apply for the standard error. In general, however, the standard error is proportional to $1/\sqrt{q}$. That is, increasing the sample size by a factor f will reduce the standard error (improve the precision of the estimate) by a factor of $\sqrt{f}$.

For example, consider a building with ten more or less identical floors with electricity used for lighting intended to be the retrofit. The building has junction boxes separated by floor. We wish to acquire an estimate of the lighting electric use per floor. The two extreme cases are (1) measuring all ten floors and (2) measuring only one floor taken at random. Sampling, which consists of monitoring a number of (but not all) floors, reduces the uncertainty as compared to (2) while also reducing the associated metering costs associated with (1) above. If the M&V contractor suggests measuring five floors only, then (1-q/Q) = (1-5/10)=0.5. A M&V protocol requiring that five floors be measured and used to determine the mean electricity use for each floor will then have an SE of $(0.5)^{1/2}$=0.7 of that of a single floor measurement. Note that when q =Q=10, then SE for sampling is zero.

B2.4.2 Other Sources of Uncertainty. Though there are several separate sources of uncertainty when dealing with analysis of observed data without sampling uncertainty present, this annex will only deal with the following: (1) measurement errors in standard and in time series data, (2) prediction uncertainty when a regression model is fit to data assumed to have no measurement error in the independent variables, and (3) multiple buildings. Another situation of interest that affects uncertainty is when analyzing results from multiple buildings using similar measurement plan and model.

A clear conceptual understanding of when these arise will now be provided. Consider a model such as: $y = a_0 + a_1 \cdot x_1 + a_2 \cdot x_2$ where the x's are the independent variables and a's are model coefficients. An uncertainty in the variable y can arise from three sources as discussed below.

a. *Measurement Errors.* This case applies when the coefficients a_0, a_1, and a_2 are known with zero uncertainty (i.e., either they are constants or are values that one can look up from tables such as steam tables, for example). The uncertainty in the derived variable y is then only due to the measurement uncertainties present in the x's. How to determine the uncertainty in y for such models or equations is given by the "propagation of errors" formulae with which most engineers are familiar (Kline and McClintock 1953). An example of this type of uncertainty is when the charging rate of the thermal energy storage system is deduced from measurements of mass flow rate and inlet and outlet temperature differences (ASHRAE 2000). The formulae dealing with propagation of errors in experimental data are relatively straightforward and general purpose numerical algorithms have been suggested (Coleman and Steele 1989).

The error sources of monitoring equipment can be further divided into (i) calibration errors, (ii) data acquisition errors, and (iii) data reduction errors (ASME 1990). These lead to essentially two types of error: a systematic or biased error (b) and a random or "white noise" error (ε). It is usually cumbersome to perform an uncertainty analysis with data having known biases. The tendency has been to remove known biases from the data prior to data analysis and only treat random errors. However, the textbook by Coleman and Steele (1989) argues that one should also explicitly include bias errors of the instrument due to precision error of the primary or reference instrument against which the field instrumentation is calibrated. The book also presents pertinent formulae to treat both bias and random errors in a rigorous fashion. If bias and random errors are uncorrelated, measurement variance is given by

$$\sigma^2_{meas}(b_m, \varepsilon_m) = \sigma^2(b_m) + \sigma^2(\varepsilon_m) \qquad \text{(B-3)}$$

where b and ε denote bias and random errors, respectively.

Correlation is more common than one might expect, and it can have a positive effect on the overall measurement uncertainty in certain instances. Consider the bias error of a calibration bath used to calibrate multiple temperature sensors used to measure delta T; the bias error of the second sensor is correlated to that of the first sensor. Accounting for the correlation reduces the overall uncertainty.

Annex A provides an exhaustive description of physical measurements, their cost and errors, as well as the calibration techniques and testing standards.

b. *Model Prediction Uncertainty.* When the x's are assumed to have no error in themselves but the coefficients a_0, a_1, and a_2 have some inherent error (as a result of identifying them from regression of measured data), we have prediction errors in the y variable under such a case since any regression model with a coefficient of determination R^2 <1 is incapable of explaining the entire variation in the regressor variable (this source of error is called *model internal prediction error*). An example of this source of uncertainty is when a regression model is used to predict building loads from outdoor temperature (T). If the measurement error in T is so small as to be negligible, then the uncertainty in predicting building loads falls in this category. This case is well treated in most textbooks (for example, Draper and Smith 1981) and even in the

HVAC literature (for example, Kissock 1993; Phelan et al. 1997)

The determination of prediction errors from using regression models is subject to different types of problems. The various sources of error can be classified into three categories (Reddy et al. 1998):

- (b-i) Model mis-specification errors, which are due to the fact that the functional form of the regression model is usually an approximation of the true driving function of the response variable. Typical causes are (i) inclusion of irrelevant regressor variables or non-inclusion of important regressor variables (for example, neglecting humidity effects); (ii) assumption of a linear model, when the physical equations suggest nonlinear interaction among the regressor variables; and (iii) incorrect order of the model, i.e., either a lower order or a higher order model than the physical equations suggest. Engineering insight into the physical behavior of the system helps minimize this type of error.
- (b-ii) Model prediction errors that arise due to the fact that a model is never "perfect." Invariably a certain amount of the observed variance in the response variable is unexplained by the model. This variance introduces an uncertainty in prediction. In essence, this uncertainty arises because even though the "exact" functional form of the regression model may be known, the model parameters are random variables as a result of randomness in the regressor and response variables.
- (b-iii) Model extrapolation errors, which arise when a model is used for prediction outside the region covered by the original data from which the model has been identified. Models identified from short data sets, which do not satisfactorily represent the annual behavior of the system, will be subject to this source of error. The prediction of long-term building loads from short-term in-situ tests will suffer from this type of error. There are a few papers (for example, Kissock et al. 1993; Katipamula et al. 1995; Reddy et al. 1998; Reddy et al. 1999) that have investigated this issue of extrapolation errors. We cannot quantify this error in statistical terms alone, but experimental conditions to be satisfied that are likely to lead to accurate predictive models have been suggested. For example, for climate-dependent loads, it is preferable to monitor during the swing seasons when a wider range of climatic variability is experienced.

c. *Multiple Buildings.* The use of results from multiple buildings using a similar measurement plan and model can reduce the uncertainty due to random errors in measurement or modeling. If the errors are random, then the standard deviation of the population of size P units provides a measure of the error in estimating the mean (or total) of the values. This is because the population can be viewed as a sample of another, infinite hypothetical population, in which the random errors sum to zero (by definition). Then the formula given by equation B-2, with Q equal to infinity and q set to P, is the standard error due to the random errors of the results for the individual buildings:

$$SE(y) = \sqrt{\sum_{i=1}^{P} (y_i - \bar{y})^2 / P} \tag{B-4}$$

The above equation is extremely useful in estimating the effects of random variables when designing the model, since the use of multiple units may mean that some random effects can be ignored in modeling. This has often been applied to large residential projects to enable the elimination of the need to model random variables such as occupancy changes.

B2.5 Combining Components of Uncertainty. If the savings estimate S is a sum of several independently estimated components C,

$$S = C_1 + C_2 + C_3 + \ldots + C_p , \tag{B-5a}$$

the standard error of the estimate is given by

$$\Delta(S) \equiv \surd[SE(C_1)^2 + SE(C_2)^2 + SE(C_3)^2 + ... + SE(C_p)^2]. \tag{B-5b}$$

If the savings estimate S is a product of several independently estimated components C,

$$S = C_1 \times C_2 \times C_3 \times \ldots \times C_p \tag{B-6a}$$

the relative standard error of the estimate is given approximately by

$$\Delta(S) \equiv SE(S) \sim S \times \sqrt{\left[(SE(C_1)/C_1)^2 + (SE(C_2)/C_2)^2 + (SE(C_3)/C_3)^2 + (SE(C_p)/C_p)^2\right]} . \tag{B-6b}$$

The requirement that the components be independently estimated is critical to the validity of these formulas. Independence means that random errors affecting one of the components are unrelated to the errors that affect the other components. In particular, the different components would not be estimated by the same regression fit or from the same sample of observations.

B2.6 Concluding Remarks. Both sources (a) and (b-iii) and (c) are likely to introduce bias and random error in the predictions. If ordinary least squares (OLS) regression is used for parameter estimation and if the model is subsequently used for prediction, error due to sources (b-i) and (b-ii) will be purely random with no bias. Thus, models identified from short data sets and used to predict seasonal or annual energy use are affected by both (a) and (c) sources of error. The best way to minimize all the above sources of error is to calibrate the instruments properly, increase the number of data observations (or sampling points), and take observations under operating conditions that cover the entire range of variation of system operation. Since ASHRAE Guideline 14 requires that data (either in the form of utility bills or monitored data) span at least nine months and capture the annual extremes in climatic variability at the specific location, the bias due to this effect is likely to be small and will not be discussed further in this annex.

The accuracy of a savings estimate can be improved in two general ways. One is by reducing biases, by using better information, or by using measured values in place of assumed or stipulated values. The second way is by reducing the random errors, either by increasing the sample sizes, using a more efficient sample design, or applying better measurement techniques. In most cases, improving the accuracy by any of these means requires the investment of more money. This investment must be justified by the value of the improved information.

The value of improved accuracy to ESCOs or owners depends on how they expect this improvement to affect them. The most obvious effect would be a change in the payments made, but there are other reasons for an interest in more accurate savings estimates. Owners may value a higher level of monitoring because they believe that the monitoring requirement itself will result in improved performance. Such improvement could be related to a commissioning effort or to higher quality work by installers and operators as a result of their awareness of the monitoring and/or feedback from this information. ESCOs may value more accurate savings determination for its value in enhancing their credibility. Both owners and ESCOs may value the improved understanding that will affect similar projects they might undertake.

In cases where the overriding reason to consider additional accuracy is for its effect on payments, the value of the improved estimate to the owner and ESCO depends on what each party believes will be the effect of improved measurements. If both parties believe that the savings will be close to the nominal level, and neither has asymmetric risks associated with errors in the savings, it may be reasonable to do no monitoring and accept a stipulated savings agreement. On the other hand, if the owner believes that the nominal level that would be stipulated is higher than what will actually be achieved, the owner will have an incentive to invest more money in monitoring. Likewise, if the ESCO believes that the nominal level that would be stipulated is lower than what will actually be achieved, the ESCO will have an incentive to invest more money in monitoring. In either case, however, it would not make sense to invest more in to improved accuracy than the expected change in the payment, unless there are other reasons for the monitoring. This issue is discussed in more detail by Goldberg (1996).

B2.7 Scope of Annex. Clause 5 of this guideline identifies three approaches for savings measurement:

1. Whole building approach
2. Retrofit isolation (which can be further subdivided into with and without interaction)
3. Calibrated simulation

There is still no broad consensus as to how to determine uncertainty or risk levels based on a calibrated simulation approach. Hence this annex has addressed this issue at a rather superficial level. A short discussion of this issue and preliminary recommendations as to how to ascertain or estimate uncertainty is provided in clause B7 of this annex.

The scope of this annex will include the first two approaches along with another approach using utility bill data where the savings uncertainty can be estimated at the project proposal phase prior to implementation of the ECM. Though one does not have measured data at this stage, an analysis involving utility bill data along with the estimated savings fraction can provide an indication of what type of savings measurement approach to adopt later on, which in turn will impact the cost associated with the M&V process.

Further, there are three types of data that one could gather in the framework of any of the three M&V approaches adopted: spot measurements, monthly or utility bill data, and hourly/daily data. Table B-1 is a tabulation of the above categories of M&V approaches for each of the four types of data. The table also includes the case when the uncertainty evaluation is being done at the project proposal phase. The pertinent cases addressed in this appendix are denoted as "Yes," while those denoted as "No" imply that further research/development/consensus needs to be reached before they could be included in ASHRAE Guideline 14. Note that all instances where less than a year of data are missing have been excluded in the current document.

TABLE B-1
Table Listing Various Analysis Methods and Cases Treated

				Type of M&V Approach →			
Type of Data			**Project Proposal**	**Whole Building**	**Retrofit Isolation (Without Interaction)**	**Retrofit Isolation (With Interaction)**	**Calibrated Simulation**
Spot measurements	1a	Pre utility data	Yes	No	No	No	No
	1b	Pre & post	N/A	No	Yes	Yes	No
Continuous monthly or utility bill data	2a	Pre & post >1 yr	N/A	Yes	Yes	No	Yes
	2b	Pre & post <1 yr	N/A	No/Yes	Yes/No	Yes/No	Yes
Continuous hourly/ daily data	3a	Pre & post > 1 yr	N/A	Yes	Yes	Yes	Yes
	3b	Pre & post < 1 yr	N/A	No/Yes	Yes/No	Yes/No	Yes
(Yes—case treated here in this annex; No—case not treated here; N/A—not applicable)							

B3 Background in Savings Uncertainty

A proper uncertainty analysis can be very complex and cumbersome especially if the potential user strives to be very meticulous. There are four good references in the HVAC literature: ASHRAE Guideline 2-1986 (ASHRAE 1990), ASHRAE RP-827 (Phelan et al. 1997), Annex B of ASHRAE Standard 150 on cool storage performance testing (ASHRAE 2000), and a report by Kammerud et al. (1999). The former three address specific issues with regard to engineering uncertainty analysis, while the last reference is much wider in its overall scope in that economic uncertainties and year-to-year variability in building operation and loads are also considered, while the engineering uncertainty issues are treated in a less rigorous fashion.

Given, say, building energy use data, either utility bills or monitored data, both prior to and after the ECM, the procedure used to determine savings is to normalize the data for any changes in conditioned area or occupancy changes and to identify a pre-ECM model against climatic conditions, often the outdoor dry-bulb temperature being the only regressor variable used. There are two variants used to determine savings depending on how one makes use of the post-ECM data:

(a) The "Normalized Annual Average Savings" approach, which involves developing an outdoor dry-bulb temperature-based post-ECM regression model and using long-term average dry-bulb temperature values over several years to drive this model along with the baseline model (Fels 1986; Fels et al. 1995; Ruch and Claridge 1993)

(b) The "actual savings" over a certain time period where the baseline model is driven with actual monitored outdoor temperature under post-ECM conditions and the sum of the differences between these values and the observed post-ECM values is taken to be the energy savings over that time period (Kissock et al. 1992; NEMVP 1996).

In this annex, we are concerned primarily with (b) above. Uncertainty is a function of measurement error and inaccuracy in the mathematical regression model. Usually the latter source of uncertainty is of greater importance. However, this may not always be true, and so the previous clauses of this annex covered the sources of measurement error as well.

Work has been done to establish the sound statistical limits for gauging the goodness-of-fit of the baseline model. Perhaps the most widely used criteria are those suggested by Reynolds and Fels (1988). They proposed (i) that models with R^2 values >0.7 and CV < 7% or (ii) models with low R^2 values and CV < 12% be considered reliable models, while models not satisfying at least one of these criteria be considered poor, and that data from buildings with poor baseline models should be discarded while performing DSM evaluations. These cutoffs appear arbitrary, since no clear rationale for their choice is provided. Further, there is no basis for development of absolute statistical cutoff criteria since baseline model development is not an end in itself. The more relevant criterion for determining whether a baseline model is acceptable or not is the fractional uncertainty in savings measurement, dE_{save}/E_{save}. For example, consider two cases: one where it is estimated that the retrofit is likely to reduce energy use by 30% and another where the anticipated energy reduction is only 10%. Assume that a baseline model for the first case produces a particular choice of required uncertainty in savings (e.g., $dE_{save}/E_{save}=0.1$). Intuitively, a much better model would be needed in the second case to produce the same uncertainty. A physically based criterion such as this would provide more meaningful evaluations of ECM programs. This annex presents this physical concept in statistical and mathematical terms following a paper by Reddy and Claridge (2000).

B4 Uncertainty Formulae

B4.1 General Approach. Conceptually, actual savings (as against "normalized" savings) E_{save} over m days (or months, depending on the type of energy use data available) into the retrofit period are calculated as follows (Reddy et al. 1998):

$$\sum_{j=1}^{m} E_{save,j} = \sum_{j=1}^{m} \hat{E}_{\mathrm{Pre},j} - \sum_{j=1}^{m} E_{Meas,j} \tag{B-7a}$$

$$E_{save,m} = \hat{E}_{Pre,m} - E_{Meas,m} \tag{B-7b}$$

where

m = number of periods (hour, day, week, or month) in the post-retrofit period,

$\hat{E}_{\mathrm{Pre}}$ = pre-retrofit energy use predicted by the baseline model per period, and

E_{Meas} = measured post-retrofit energy use per period.

With the assumption that model prediction and measurement errors are independent, the total variance is the sum of both:

$$(\Delta E_{save,m})^2 = (\Delta\hat{E}_{\mathrm{Pre},m})^2 - (\Delta E_{Meas,m})^2 \tag{B-8a}$$

It is obvious that total prediction uncertainty increases with m, i.e., as the post-retrofit period gets longer. However, as the amount of energy savings also increases with m, a better indicator of the uncertainty is the fractional uncertainty defined as the energy savings uncertainty over m periods divided by the energy saving over m periods:

$$\frac{\Delta E_{save,m}}{E_{save,m}} = t \cdot \left\{ \frac{(\Delta\hat{E}_{Pre,m})^2}{(\hat{E}_{Pre,m})^2 \cdot F^2} + \frac{(\Delta E_{Meas,m})^2}{(\hat{E}_{Pre,m})^2 F^2} \right\}^{1/2} \tag{B-8b}$$

where F is the ratio of energy savings to pre-retrofit energy use, i.e.,

$$F = (\hat{E}_{\mathrm{Pre},m} - E_{Meas,m}) / \hat{E}_{\mathrm{Pre},m} \tag{B-9}$$

and t is the t-statistic

Equations (B-8a) and (B-8b) are generic formulations of equations that provide a means of calculating the fractional uncertainty in the "actual" savings, which consists of a term representative of the regression model prediction uncertainty and another term representative of the measurement error in the post-retrofit energy use. Note that the measurement error in the pre-retrofit energy use is inherently contained in the model goodness-of-fit parameter (namely, the mean square error (MBE) statistic and should not be introduced a second time.

A more computationally useful form is to approximate equation (B-8b) as

$$\frac{\Delta E_{save,\,m}}{E_{save,\,m}} = t \cdot \frac{[\Delta \hat{E}_{pre,m} + \Delta(m \cdot \bar{E}_{meas})^2]^{1/2}}{m \cdot \bar{E}_{pre} F} \tag{B-8c}$$

where $\Delta \bar{E}_{meas,\,m}$ is the uncertainty in measuring the mean post-retrofit energy use over m periods. This would not only depend on the type of instrument used but also on the ratio of $\bar{E}_{meas}$ to the full-scale reading of the instrument since instrument errors are usually specified in terms of their full-scale reading.

In case the measurement uncertainty is small (for example, when electricity is the energy channel, its associated error is of the order of 1-2%), the fractional uncertainty in our savings measurement is then:

$$\frac{\Delta E_{save,\,m}}{E_{save,\,m}} = t \cdot \frac{(\Delta \hat{E}_{pre,\,m})}{m \cdot \bar{E}_{pre} F} \tag{B-8d}$$

We would like to cast this expression into a more useful form for which certain simplifying assumptions need to be made. Three cases are treated:

- weather-independent models, when, for example, lighting retrofits are being evaluated,
- weather-based regression models with uncorrelated model residuals as assumed when analyzing utility bills, and
- weather-based regression models with serial correlation often encountered with models based on hourly, or in some cases with daily, data (Ruch et al. 1993).

B4.2 Weather-Independent Models. When the energy use is independent of weather and other variables, such as lighting retrofits, a mean model representative of the average value can be determined from the data. Equation (B - 8d), assuming no measurement uncertainty, can then be rewritten as:

$$\frac{\Delta E_{save,\,m}}{E_{save,\,m}} = t \cdot \frac{CVSTD}{m^{1/2} F} \tag{B-10}$$

where CVSTD is the coefficient of variation of the standard deviation of the pre-retrofit data points.

B4.3 Weather Models with Uncorrelated Residuals

Using the standard equation for regression model prediction interval of an individual observation extended to apply to the sum of m individual observations, Reddy and Claridge (2000) proposed the following simplified equation for fractional savings uncertainty over m time periods:

$$\frac{\Delta E_{save,\,m}}{E_{save,\,m}} = t \cdot \frac{1.26 \cdot RMSE\left(m + \frac{m}{n} + \frac{m}{n}\right)^{1/2}}{m \bar{E}_{pre} F} \tag{B-11}$$

where

$$RMSE = \left[\sum_{i=1}^{n} (E_i - \hat{E}_i)^2_{pre} / (n-p)\right]^{1/2} \tag{B-12}$$

n and m = number of observations in the baseline (or pre-retrofit) and the post-ECM periods, respectively, and the multiplier 1.26 is an empirical coefficient,

T_o and T_i = average outdoor dry-bulb temperature values during model identification (i.e., pre- retrofit) and post-retrofit periods, respectively, and

p = number of model parameters. Note: This should not be confused with the number of independent or regressor variables. For example, a simple model such as $y = a+b \cdot x$ has one independent variable and two model parameters (i.e., a and b). In the change point model y = $a+b \cdot DD(c)$ where $DD(c)$ is the degree-days to the base c, the model has one regression variable (i.e., DD) and three model parameters (a, b, and c), which are identified by the regression analysis.

Finally, equation (B-12) can be expressed in terms of the standard CVRMSE statistic (denoted by CV below) as

$$\frac{\Delta E_{save,\,m}}{E_{save,\,m}} = t \cdot \frac{1.26 \cdot CV\left[\left(1 + \frac{2}{n}\right)\frac{1}{m}\right]^{1/2}}{F} \tag{B-13a}$$

where

$$\cong t \cdot \frac{1.26 \cdot CV}{m^{1/2} F} \text{ when } n \text{ is large (say, } n > 60). \tag{B-13b}$$

Note that the above expression yields the fractional energy savings uncertainty at one standard error (i.e., at 68% confidence level where $t = 1$). For other confidence levels, say 90%, the bounds have to be multiplied by the student t-statistic evaluated at 0.05 significance level and (n-p) degrees of freedom (Draper and Smith 1981). In case the analyst wishes to include the effect of measurement errors also in the analysis, he or she should use equation (B-8c). Equation (B-13) provides a measure of one term only, i.e., $\Delta(\hat{E}_{pre,\,m})/(m \cdot \bar{E}_{pre} \cdot F)$ of equation (B-8c).

B4.4 Weather-Dependent Models with Correlated Residuals. Note that equations (B-13a) and (B-13b) are appropriate for regression models without serial correlation in the residuals. This would apply to models identified from utility (e.g., monthly) data. When models are identified from hourly or daily data, previous studies (see, for example, Ruch et al. 1993) have shown that serious autocorrelation often exists. These autocorrelations may be due to (i) "pseudo" patterned random behavior due to the strong autocorrelation in the regressor variables (for example, outdoor temperature from one day to the next is correlated) or (ii) to seasonal operational changes in the building and HVAC system not captured by an annual model. Consequently, the uncertainty bands have to be widened appropriately. Accurate expressions for doing so have been proposed by Ruch et al. (1993),

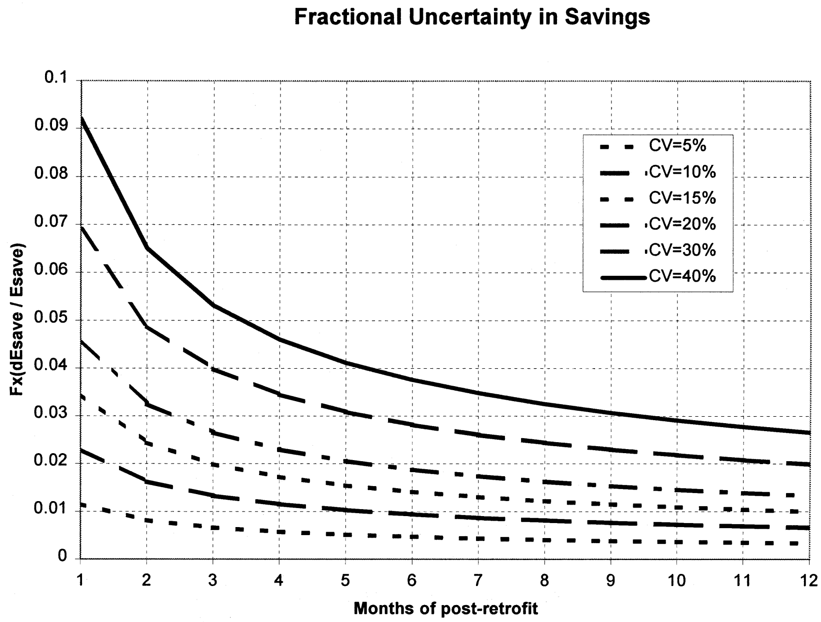

Figure B-1 Fractional uncertainty in savings with varying CVs and months of post-retrofit data.

which are, unfortunately, mathematically demanding. A simplified approach is more appropriate in ASHRAE Guideline 14 as proposed by Reddy and Claridge (2000).

From statistical sampling theory, the number of independent observations n' of n observations with constant variance but having a lag 1 autocorrelation is equal to ρ

$$n' = n \cdot \frac{1-\rho}{1+\rho}\,. \tag{B-14}$$

By extension, a simplified and intuitive way of modifying equations (B-13) in the presence of serial autocorrelation is to correct the CV by the new degrees of freedom n' and to replace n by n':

$$\frac{\Delta E_{save,\,m}}{E_{save,\,m}} = t \cdot \frac{1.26 \cdot CV\left[\frac{n}{n'}\left(1+\frac{2}{n'}\right)\frac{1}{m}\right]^{1/2}}{F} \tag{B-15}$$

Again, the second term in the right-hand side of equation (B-8c) should be included along with the above in case the analysts wish to include instrument measurement uncertainty in the analysis.

A short discussion on how to compute the autocorrelation coefficient of model residuals is provided here. The autocorrelation coefficient ρ of a time series data stream provides a measure of the extent to which an observation is correlated with its immediate successor. The coefficient ρ, which is usually at lag 1, is easily deduced by duplicating the time series data of model residuals onto another column of your worksheet with the time stamp displaced by one time interval. The square root of the R^2 value between both these data streams is the coefficient ρ. Note that only for daily or hourly data series is there a need to make corrections to the uncertainty formulae presented below. In certain cases, this coefficient is so low (say, $\rho < 0.5$ that the effect of serial autocorrelation in the regression model residuals can be ignored.)

B5 Discussion and Examples

Equations (B-10), (B-13), and (B-15) now provide a more rational means of evaluating the accuracy of our baseline model to determine savings. It is important to realize the importance of the degrees of freedom (*n-p*) of the regression model. This impacts not only the RMSE and the CV (see equation B-12) but also the value of the t-statistic used to compute the uncertainty, not at 68% (as when $t = 1$), but, say, at 90% confidence level. Consider a case when 12 utility bills are fit with a two-parameter model. Then n-p=12-2=10. Referring to clause 5.2.11, we note from Table 5-1 that for 90% confidence level at 10 degrees of freedom, $t = 1.81$.

Figure B1 illustrates how equation (B-13) can be used. Say we have a change point baseline model based on daily energy use measurements with a CV =10% and we wish to assess the uncertainty in our savings six months into the post-retrofit period for a retrofit measure that is supposed to save 10% of the pre-retrofit energy use (i.e, $F = 0.1$). Then for m = 6 months = 182.5 days, and CV=10%, the y-ordinate value from Figure B1 is 0.01, i.e., fractional uncertainty ($\Delta E_{save,m}$/ $\Delta E_{save,m}$ = 100* (0.01 / 0.1) = 10%. On the other hand, if a baseline model is relatively poor, say CV = 30%, and the retrofit is supposed to save 40% of the pre-retrofit energy use, then from Figure B1, $\Delta E_{save}/E_{save}$ = 100* (0.028 / 0.4) = 7%. Hence, the first model, which has a CV value three times lower than that of the second model, leads to a larger fractional uncertainty in the savings than the second case. The above example serves to illustrate how viewing the retrofit savings problem in the perspective of the above discussion is more relevant than merely looking at the baseline model goodness-of-fit only. Note that this figure is based on 68% confidence level (i.e., $t = 1$). The user can refer to any standard statistical

TABLE B-2
Fractional Energy Savings Uncertainty at 68% Confidence Level After One Year as Given By Equation (B-13a) with the Baseline Model Identified from Year-Long Utility Bills ($m = n = 12$) and No Residual Autocorrelation

	F				
CV	0.05	0.1	0.2	0.3	0.4
0.05	0.393	0.196	0.098	0.065	0.049
0.1	0.786	0.393	0.196	0.131	0.098
0.15	1.179	0.589	0.295	0.196	0.147
0.2	1.571	0.786	0.393	0.262	0.196
0.25	1.964	0.982	0.491	0.327	0.246
0.3	2.357	1.179	0.589	0.393	0.295

textbook in order to find the required t-statistic multiplier appropriate for the particular application (i.e, the number of degrees of freedom and the confidence level chosen).

The variation of the fractional uncertainty ($\Delta E_{save}/E_{save}$) with CV, n, m, and F is of interest to energy managers and ESCOs while negotiating energy conservation service contracts. If utility bills are the means of savings verification and if year-long pre- and post-retrofit data are available, then Table B-2 provides an indication of how ($\Delta E_{save}/E_{save}$) varies with CV and F. For example, if both negotiating parties are comfortable with a fractional uncertainty in energy savings of 15% at the 90% confidence level, then this translates to a level of (15/1.833) = 8.2% or 0.082 (see Table B-2 for an explanation of the coefficient 1.833, which is the t-statistic). Further, if the retrofits are expected to save 20% (i.e., $F = 0.2$), then a baseline model with a CV of less than 5% is required to satisfy the expectations of savings verification when one year of pre-retrofit and one year of post-retrofit utility billing data are available.

Table B-3 provides the same information as Table B-2 but assumes that daily monitored data are available for savings verification (e.g., we now have 365 data points instead of 12 data points only during either period) and that no residual autocorrelation is present (i.e., $\rho = 0$). For the above illustrative case, a baseline model with up to 30% CV will still prove satisfactory.

The two-tailed t-value for 9 degrees of freedom (12 utility bills modeled with a 3-P change point model) at 90% confidence level is 1.833.

The two-tailed t-value for 9 degrees of freedom (12 utility bills modeled with a 3-P change point model) at 90% confidence level is 1.645.

If the model residuals exhibit autocorrelated behavior, then equation (B-15) should be used to determine fractional savings uncertainty. Since an extra variable, namely, ρ, is present, it is better to look at how the variable $[(\Delta E_{save}/E_{save})\cdot F]$ varies with ρ (Table B-4). The numbers below $\rho = 0$ have a direct correspondence to those given in Table B-3. For example, if CV = 0.2, from Table B-4, $[(\Delta E_{save}/E_{save})\cdot F) = 0.013$. Further, if $F = 0.2$, then $(\Delta E_{save}/E_{save}) = 0.013/0.2 = 0.065$, which is almost identical to the value of 0.066 shown in Table B-3 for CV = 0.2 and $F = 0.2$.

TABLE B-3
Fractional Energy Savings Uncertainty at 68% Confidence Level After One Year as Given By Equation (B-13a) with the Baseline Model Identified from Year-Long Daily Monitored Data ($m = n = 365$) and No Residual Autocorrelation

	F				
CV	0.05	0.1	0.2	0.3	0.4
0.05	0.066	0.033	0.017	0.011	0.008
0.1	0.132	0.066	0.033	0.022	0.017
0.15	0.198	0.099	0.050	0.033	0.025
0.2	0.265	0.132	0.066	0.044	0.033
0.25	0.331	0.165	0.083	0.055	0.041
0.3	0.397	0.198	0.099	0.066	0.050

TABLE B-4
The Product of Fractional Energy Savings Uncertainty at 68% Confidence Level and Savings Fraction $(\Delta E_{save}/E_{save})\cdot F$ After One Year as Given by Equation (B-15) with the Baseline Model Identified from Year-Long Daily Monitored Data ($m = n = 365$)

	ρ				
CV	0	0.5	0.75	0.85	0.95
0.05	0.003	0.006	0.009	0.012	0.023
0.1	0.007	0.012	0.018	0.024	0.045
0.15	0.010	0.017	0.027	0.036	0.068
0.2	0.013	0.023	0.036	0.048	0.091
0.25	0.017	0.029	0.044	0.060	0.113
0.3	0.020	0.035	0.053	0.072	0.136

We note, as expected, from Table B-4 that $[(\Delta E_{save}/E_{save})\cdot F]$ increases as ρ increases. For example, for the same case of CV = 0.2 and $F = 0.2$, and for $\rho = 0.85$, $(\Delta E_{save}/E_{save}) = 0.048 / 0.20 = 0.24$, which is about twice the value found when $\rho = 0$. The above discussion illustrates how the time scale of data and the presence of serial autocorrelation affect fractional savings uncertainty and have direct bearing on energy savings verification.

B6 Implication Toward Required Level of M&V

Consider a situation where the energy manager of a certain facility wishes to reduce the energy bill by having certain ECMs performed by an ESCO. Further assume that utility bills of the facility are available for at least one year but that no submetered data are available. The statistical expression given by equations (B-10) and (B-13) can be used to directly provide an indication as to whether submetering is necessary or not. Thus, based on utility bills prior to the implementation of the ECM, one can acquire an indication of whether utility bill analysis is adequate to verify the intended retrofit savings.

As mentioned earlier, the selection of the particular value of ($\Delta E_{save}/E_{save}$) depends on the energy manager and the ESCO while negotiating the energy conservation contract.

Assume that both parties have reached a mutually agreeable value and that the energy savings fraction F has also been determined by an audit. Equation (B-13) is then used to determine the maximum CV (called CV_{max}) of the baseline model. The utility bills of the baseline are then fit by a model. If the model $CV < CV_{max}$, then no submetering is necessary and the required savings verification could be done from utility bill analysis only. If this is not the case, then some sort of submonitoring is required. Let us illustrate this with utility bill data of gas and electricity use at six Army bases shown in Table B-5 (taken from Reddy and Claridge 2000).

Let $(\Delta E_{save}/E_{save}) = 0.30$ be the agreed upon uncertainty fraction at 90% confidence level and expected savings fraction $F = 0.2$. Then for one year of pre-retrofit and one year of post-retrofit data (e.g., one year after the retrofits), $n = m = 12$. Since the t-statistic is equal to 1.833, the fractional uncertainty at 68% = 0.3/1.833 = 16.4%. Substituting these in equation (B-13), CV_{max} = 8%. From Table B-5, we note that only for two cases (electricity use at AB1 and AB4) are the CV values sufficiently less than 8% so as not to require submonitoring. There are five more models with CV values within plus/minus two percentage points, and whether submonitoring is required or not is negotiable. In the remaining five cases, there is a definite need to perform submonitoring if the desired confidence in the resulting savings is to be satisfied.

B7 Calibrated Simulation

As described in clause 6.3 of this guideline, calibrated simulation is an appropriate method to consider when one or more of the following conditions are present:

1. No pre-retrofit whole building hourly monitored data other than utility bills are available, while monitored post-retrofit data are available.
2. Retrofit measures interact with other building systems, and it is desired to account for those interactions when savings are reported.
3. Only whole-building energy use data are available, and the M&V calls for verifying savings due to individual retrofits.

ASHRAE Guideline 14 allows all three cases to be treated. It suggests that when only whole building energy use is being monitored, that uncertainty be reported solely for this energy use, and that no attempt be made to estimate uncertainty at a more disaggregated level or for individual retrofits. A building energy simulation model once calibrated with hourly data would still differ from the measured values. This difference between modeled and measured hourly data allows the analyst to compute a CV just as when a regression model approach was adopted. It is this CV that will be used along with equations (B13) or (B15) to estimate the fractional uncertainty.

B8 Nomenclature

E = energy use, baseline energy use per unit time interval (month, day, hour)

F = ratio of the energy savings to baseline energy use

m = number of post-retrofit observation points (months, days, hours, ...)

n = number of pre-retrofit observation points (months, days, hours, ...)

p = number of model parameters (= k+1)

Q = number of units in the total population

q = number of units in the sample

T = outdoor dry-bulb temperature

t = t-statistic

$\overline{X}$ = mean value of X

$\hat{X}$ = model-predicted value of X

α = significance level

b = bias error

ε = random error

σ = standard deviation

σ^2 = estimated variance of the model error

ρ = autocorrelation coefficient

CV = coefficient of variation (either the CVRMSE or the CVSTD)

ΔE = uncertainty in E

SE = standard error

MSE = mean square error

$RMSE$ = root mean square error

STD = standard deviation

Subscripts

Post = post-retrofit

Pre = pre-retrofit or baseline

TABLE B-5
Application to Utility Bill Energy Use Data from Six Army Bases Nationwide (Adapted from Reddy et al. 1997)

Army Base	Model Type	R^2	CV (%)
Electricity			
AB1	4P-HC	0.95	4.7
AB2	Mean	-	8.0
AB3	3P-H	0.66	10.7
AB4	3P-C	0.98	5.2
AB5	3P-C	0.66	7.1
AB6	Mean	-	8.3
Gas			
AB1	3P-H	0.87	14.4
AB2	3P-H	0.94	13.7
AB3	3P-H	0.69	36.5
AB4	3P-H	0.98	10.1
AB5	3P-H	0.93	18.4
AB6	3P-H	0.69	16.2

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(This informative annex is not part of ASHRAE Guideline 14 but is provided for informational purposes only.)

ANNEX C: EXAMPLES

C1 Examples for Clause 6.1, Whole Building Approach

There are two examples applying the guideline using a whole building approach. In addition, Clause C1.3 shows a sample calculation of degree-days. The first example is a whole building prescriptive path and the second is a whole building performance path. The second example also shows a base year adjustment being implemented. Each example consists mainly of the measurement and verification plan, with additional reports showing the energy savings for one year. The measurement and verification plan includes the following:

a. The selected measurement approach and compliance path.

b. Baseline period data:

- The baseline energy use and demand taken from the utility bills, including the calculation of the degree-days and mean temperature for each of the reading periods.
- The results of the linear regression analysis performed on the data.
- Baseline conditions.

c. The algorithm for savings determination, showing

    1. the methodology to be used for all normal sets of post-retrofit conditions,
    2. the means of dealing with each type of anomaly that was the subject of an exclusion or adjustment when developing the baseline model, and
    3. the results of the net determination bias test.

d. The measurement procedure.

e. Quality control procedures.

f. The savings reporting frequency and format.

Any comments regarding the examples will be shown in italics.

C1.1 Example Whole Building Prescriptive Path. The first example is a chronic care hospital building in which the main electric meter is not sensitive to outdoor weather and the main natural gas meter is sensitive to heating degree-days.

The Measurement and Verification Plan

a. ***The Whole Building Prescriptive Path will be used for determining savings.***

This building will undergo a comprehensive energy retrofit, which will affect lighting, heating, air-conditioning, and domestic hot water systems. The changes also include the installation and commissioning of an energy management control system using direct digital control of the largest energy-using equipment. It is anticipated that the total energy savings will be the following:

Electrical energy use	20% per year
Electrical demand	15% per year
Natural gas	25% per year

The building will be monitored for three years after completion of the retrofit.

b. Baseline period data.

The following pages show the baseline period data for each meter and the results of the linear regression with heating and cooling degree-days.

Electric meter

Weather Station: BLOORS Bloor Station, Toronto
Area: 355,500 ft2
Heating Balance Temperature: 15°C Demand Heating Balance Temperature: 15°C
Cooling Balance Temperature: 17°C Demand Cooling Balance Temperature: 17°C

Reading Date	Days	Month	CONSUMPTION [kWh]	DEMAND [kW]	Daily Consumpt. [kWh]/day	HDD [°C]	CDD [°C]	Temp [°C]
1985-Jul-17	30	S	762,300	950	25,410.0	0.0	84.5	19.7
1985-Aug-16	30	S	665,280	930	22,176.0	0.0	134.3	21.5
1985-Sep-16	31	S	623,700	990	20,119.4	8.2	91.4	19.3
1985-Oct-16	30	W	568,260	950	18,942.0	43.7	18.7	14.9
1985-Nov-15	30	W	623,700	772	20,790.0	190.3	0.0	8.7
1985-Dec-16	31	W	457,380	722	14,754.2	423.4	0.0	1.3
1986-Jan-15	30	W	665,280	752	22,176.0	618.4	0.0	-5.6
1986-Feb-14	30	W	540,540	792	18,018.0	556.9	0.0	-3.6
1986-Mar-14	28	W	526,680	761	18,810.0	509.2	0.0	-3.2
1986-Apr-15	32	W	498,960	712	15,592.5	290.1	0.1	6.0
1986-May-15	30	W	693,000	970	23,100.0	102.3	3.2	12.1
1986-Jun-16	32	S	595,980	970	18,624.4	17.6	49.5	17.3
			Totals:	364	7,221,060			

Results of linear regression, as shown below.

WINTER LINEAR REGRESSION	
base load [kWh/day]	17,444.43
weather factor [kWh/HDD]	901.2550
CV(STD)	0.399
CV(RMSE) [%]	9.30
demand base load [kW/mo]	876.08
demand weather factor [kW/HDD]	8.7329
demand CV(STD)	.204
demand CV(RMSE) [%]	3.00
SUMMER LINEAR REGRESSION	
base load [kWh/day]	19,627.11
weather factor [kWh/CDD]	-57.1751
CV(STD)	0.019
CV(RMSE) [%]	14.59
demand base load [kW/mo]	1373.31
demand weather factor [kW/CDD]	-9.0589
demand CV(STD)	0.576
demand CV(RMSE) [%]	9.56

Natural Gas Meter

Weather Station: BLOORS Bloor Station, Toronto
Heating Balance Temperature: 15°C
Cooling Balance Temperature: 15°C

Reading Date	Days	CONSUMPTION Month	[m3]	Daily Consumpt. [m3]/day	HDD [°C]	CDD [°C]	Temp [°C]
1985-Jul- 9	28	S	70,047	2,501.7	6.6	95.7	18.2
1985-Aug-13	35	S	84,010	2,400.3	0.0	218.0	21.2
1985-Sep-10	28	S	64,959	2,320.0	0.0	163.0	20.8
1985-Oct-15	35	W	96,573	2,759.2	51.3	41.1	14.7
1985-Nov-12	28	W	110,836	3,958.4	159.6	1.0	9.3
1985-Dec-10	28	W	159,144	5,683.7	353.6	0.0	2.4
1986-Jan-14	35	W	253,199	7,234.3	690.8	0.0	-4.7
1986-Feb-11	28	W	200,452	7,159.0	516.5	0.0	-3.4
1986-Mar-11	28	W	191,339	6,833.5	535.3	0.0	-4.1
1986-Apr-15	35	W	160,532	4,586.6	333.1	2.6	5.6
1986-May-13	28	W	79,885	2,853.0	99.5	14.0	11.9
1986-Jun-10	28	S	61,002	2,178.6	20.1	75.7	17.0
Totals:	364		1,531,978		2766.4	611.1	

Results of linear regression, as shown below.

WINTER LINEAR REGRESSION	
base load [m3/day]	2,300.63
weather factor [m3/HDD]	251.2343
CV(STD)	0.986
CV(RMSE) [%]	3.99
SUMMER LINEAR REGRESSION	
base load [m3/day]	2,253.18
weather factor [m3/CDD]	21.5232
CV(STD)	0.080
CV(RMSE) [%]	4.71

Baseline Conditions

The utility companies involved have a good history reading the meters regularly and accurately. There are no gaps in the baseline period of approximately June 1985 to July 1986, and it is anticipated that this will continue over the monitoring period for this project.

- Lighting—was operated manually in all areas. Corridor lights were usually shut off at 10 p.m. each evening.
- Laundry—was operated on a daily 8-hour shift, 7 days a week and no bedding outside the hospital was included.
- Kitchen—was operated on a 12-hour shift, 7 days a week, with no extra meal preparation.
- Fan schedule—the attached schedule indicates the ventilation fan schedule during the baseline period.
- Miscellaneous—there were 13 personal computers, 4 laser printers, 8 dot matrix printers, and 4 copiers on site as detailed in the attached equipment survey.

c. *Savings Algorithm.*

Electric Meter

Because the building does not have a substantial amount of electric heating or cooling equipment and the linear regression results in poor correlation of energy use and demand with heating and/or cooling degree-days, the following will be used for calculating the projected baseline:

$$E_p = E_b / days_b \times days_c$$

$$D_p = D_b$$

The savings formulas are then:

$$E_s = E_p - E_c$$

$$D_s = D_p - D_c$$

where

E_p = projected energy consumption
E_b = energy consumption in baseline month
E_c = current monthly energy consumption
E_s = monthly energy savings
$days_b$ = number of reading days in baseline month
$days_c$ = number of reading days in current month
D_p = projected monthly demand
D_b = demand in baseline month
D_c = current monthly demand
D_s = monthly demand savings

Natural Gas Meter

The linear regression results in good correlation between energy use and heating degree-days. The following will be used for determining savings:

$$E_p = E_b / days_b \times days_c\text{, for summer months}$$

$$E_p = 2300.63 \times days_c + 251.2343 \times HDD_c\text{, for winter months}$$

The savings formula is then

$$E_s = E_p - E_c$$

where

E_p = projected energy consumption
E_b = energy consumption in baseline month
E_c = current monthly energy consumption
E_s = monthly energy savings
$days_b$ = number of reading days in baseline month
$days_c$ = number of reading days in current month
HDD_c = number of heating degree days in current month

Electric Meter

NET DETERMINATION MEAN BIAS TEST

Consumption

Month	Original Base Year [kWh]	Projected Base Year [kWh]	Savings [kWh]	% Energy Saved
Jul	762,300	762,300	0	0.00
Aug	665,280	665,280	0	0.00
Sep	632,700	632,700	0	0.00
Oct	568,260	568,260	0	0.00
Nov	623,700	623,700	0	0.00
Dec	457,380	457,380	0	0.00
Jan	665,280	665,280	0	0.00
Feb	540,540	540,540	0	0.00
Mar	526,680	526,680	0	0.00
Apr	498,960	498,960	0	0.00
May	693,000	693,000	0	0.00
Jun	595,980	595,980	0	0.00
Total	7,221,060	7,221,060	0	0.00

Demand

Month	Original Base Year [kW]	Projected Base Year [kW]	Savings [kW]	% Energy Saved
Jul	950	950	0	0.00
Aug	930	930	0	0.00
Sep	990	990	0	0.00
Oct	950	950	0	0.00
Nov	772	772	0	0.00
Dec	722	722	0	0.00
Jan	752	752	0	0.00
Feb	792	792	0	0.00
Mar	761	761	0	0.00
Apr	712	712	0	0.00
May	970	970	0	0.00
Jun	970	970	0	0.00
Total			0	0.00

```
Natural Gas Meter

NET DETERMINATION MEAN BIAS TEST


            Original          Projected
             Base                             Base  Energy     %
             Year       days        HDD       Year  Savings  Energy
Month       [m3]                                           [m3]          [m3]
Saved
Jun         70,047      28            6.6       70,047            0      0.00
Jul         84,010      35            0.0       84,010            0      0.00
Aug         64,959      28            0.0       64,959            0      0.00
Sep         96,573      35           51.3       93,410       -3,162     -3.39
Oct         110,836     28          159.6       104,514      -6,321     -6.05
Nov         159,144     28          353.6       153,254      -5,889     -3.84
Dec         253,199     35          690.8       254,074         875      0.34
Jan         200,452     28          516.5       194,180      -6,271     -3.23
Feb         191,339     28          535.3       198,903       7,564      3.80
Mar         160,532     35          333.1       164,208       3,676      2.24
Apr         79,885      28           99.5       89,415        9,530     10.66
May         61,002      28           20.1       61,002            0      0.00
Total 1,531,978                                 1,531,976         2      0.00013
<============
```

The projected base year values are determined by substituting the base year reading days and heating degree-days into the savings algorithm formula(s):

$$E_p = 2300.63 \times days_c + 251.2343 \times HDD_c$$

For example, the values for November and February are found from the following:

November

$E_p = 2300.63 \times days_c + 251.2343 \times HDD_c$

$= 2300.63 \times 28 + 251.2343 \times 353.6$

$= 153254$

February

$E_p = 2300.63 \times days_c + 251.2343 \times HDD_c$

$= 2300.63 \times 28 + 251.2343 \times 535.3$

$= 198903$

d. The Measurement Procedure.

Because the energy usage and demand values are taken from the measurements made by the utility company, no special measurement procedures will be necessary.

Utility bills will be forwarded from the client to our office for entry into a computer software program that will calculate the energy use, demand, and cost savings and produce reports on a monthly basis. This monthly monitoring is expected to cost $600 annually.

e. Quality control procedures.

Quality control will be monitored by one or more of the following:

- entering of meter readings and comparison of calculated consumption versus utility-provided consumption values
- validation of billing demand from actual demand, kVA, or power factor and rate structures

All baseline authorization, access to change data, and record keeping will follow internal ISO procedure and work instructions.

f. The savings reporting frequency and format.

Savings will be reported on a monthly basis and sample reports are shown below.

Electric Meter

ENERGY SAVINGS REPORT

Period: 1990.01.01 to 1990.12.31

Consumption

Month	Projected Base Year [kWh]		Current Year [kWh]		Savings [kWh]	% Energy Saved
Jan	644,389	508,662	135,727	21.06		
Feb	541,600	480,942	60,658	11.20		
Mar	527,475	421,344	106,131	20.12		
Apr	483,880	478,170	5,710	1.18		
May	686,687	442,134	244,553	35.61		
Jun	716,320	546,084	170,236	23.77		
Jul	784,880	568,260	216,620	29.60		
Aug	792,690	594,594	198,096	24.99		
Sep	703,850	686,070	17,780	2.53		
Oct	599,705	460,152	139,553	23.27		
Nov	654,079	433,818	220,261	33.68		
Dec	526,874	540,540	-13,665	-2.29		
Total	7,662,431	6,160,170	1,501,661	19.60		

Demand

Month	Projected Base Year [kW]		Current Year [kW]		Savings [kW]	% Energy Saved
Jan	752	685	57		7.58	
Feb	792	690	92	11.62		
Mar	761	682	79		10.38	
Apr	712	605	107		15.03	
May	970	820	150	15.46		
Jun	970	810	160	16.49		
Jul	950	820	130	13.68		
Aug	930	800	130		13.98	
Sep	990	840		150	15.15	
Oct	950	826	124	13.05		
Nov	772	685	87	11.27		
Dec	722	670	52	7.20		
10,271				1,179		11.48

Natural Gas Meter

ENERGY SAVINGS REPORT

Month	Projected Base Year [m3]		Current Year [m3]		Savings [m3]	%Current Energy Saved	HDD [°C]
Jan	208,149	178,282	29,866	14.35	508.0		
Feb	189,281	138,093	51,188	27.04	497.0		
Mar	139,235	111,343	27,892	20.03	297.8		
Apr	121,096	93,100	27,996	23.12	161.5		
May	74,567	43,648	30,919	41.47	40.5		
Jun	72,548	40,503	32,045	44.17	0.0		
Jul	67,208	36,665	30,543	45.46	0.0		
Aug	81,198	45,710	35,488	43.71	0.8		
Sep	76,074	54,262	21,812	28.67	46.4		
Oct	140,466	108,227	32,239	22.95	238.6		
Nov	137,376	111,102	26,274	19.13	290.4		
Dec	180,261	139,113	41,148	22.83	461.1		
Total	1,487,464	1,100,048	387,415	26.05	2,542.0		

C1.2 Example Whole Building Performance Path

The second example is an active treatment hospital building in which the main electric meter is sensitive to cooling degree-days and the main natural gas meter is sensitive to heating degree-days.

The Measurement and Verification Plan

a. ***The whole building performance path will be used for determining savings.***

This building will undergo a comprehensive energy retrofit that will affect lighting, heating, air-conditioning, and domestic hot water systems. The changes also include the installation and commissioning of an energy management control system using direct digital control of the largest energy-using equipment. It is anticipated that the total energy savings will be:

Electrical energy use	20% per year
Electrical demand	15% per year
Natural gas	25% per year

The building will be monitored for three years after completion of the retrofit.

b. Baseline period data.

The following pages show the baseline period data for each meter and the results of the linear regression with heating and cooling degree-days.

Baseline Conditions

The utility companies involved do not have a good history reading the meters regularly and accurately. There are no gaps in the baseline period of approximately September 1995 to August 1996, and it is anticipated that this will continue over the monitoring period for this project. In addition, the chiller was not working for a three-week period in May 1996 and this point must be excluded from the regression model. Hence, the whole building performance path will be used for determining savings in this building.

- Lighting—was operated manually in all areas except for the three meeting rooms, where occupancy sensors have been installed. Corridor lights were usually shut off at 10 p.m. each evening.
- Laundry—was operated on a daily 8-hour shift, 7 days a week and no bedding outside the hospital was included.
- Kitchen—was operated on a 12-hour shift, 7 days a week, with extra meal preparation every quarter for a regularly scheduled meeting.
- Fan schedule—the attached schedule indicates the ventilation fan schedule during the baseline period.
- Miscellaneous—there were 33 personal computers, 14 laser printers, 1 large dot matrix and 6 inkjet printers, and 8 copiers on site as detailed in the attached equipment survey. All the computers were linked in a local area network operated by the IT Department.

Electric Meter

```
Weather Station:       PITTSB Pittsburgh, Pennsylvania
Heating Balance Temperature:  56°F    Demand Heating Balance Temperature:   56°F
Cooling Balance Temperature:  56°F    Demand Cooling Balance Temperature:   56°F
```

Reading Date	Days	Month	CONSUMPTION [kWh]	--- DEMAND ------ Mon	Billed [kW]	Actual [kW]	Daily Consumpt. [kWh]/day	HDD [°F]	CDD [°F]	Temp [°F]	Demand PKHDD [°F]	Demand PKCDD [°F]
1995-Oct-10	29	S	261,500	S	526	526	9,017.2	12.0	186.5	62.0	6.5	17.0
1995-Nov- 9	30	S	237,500	S	496	496	7,916.7	210.0	59.5	51.0	27.0	9.0
1995-Dec-11	32	W	246,000	W	397	397	7,687.5	675.5	0.0	34.9	46.0	0.0
1996-Jan-10	30	W	215,000	W	378	378	7,166.7	953.0	0.0	24.2	42.5	0.0
1996-Feb- 9	30	W	221,000	W	381	381	7,366.7	890.0	0.0	26.3	54.5	0.0
1996-Mar-11	31	W	231,000	W	394	394	7,451.6	751.5	1.0	31.8	45.5	1.0
1996-Apr-10	30	W	237,000	W	478	478	7,900.0	487.0	0.0	39.8	29.5	0.0
1996-May-10	30	S	263,000	S	518	518	8,766.7	102.5	104.5	56.1	18.0	14.5
1996-Jun-10	31	X	205,500	X	502	502	9,532.3	50.0	262.0	62.8	14.5	24.5
1996-Jul-10	30	S	337,500	S	621	621	11,250.0	0.0	501.5	72.7	0.0	26.0
1996-Aug- 9	30	S	336,500	S	581	581	11,216.7	0.0	436.5	70.6	0.0	22.0
1996-Sep-10	32	S	354,500	S	587	587	11,078.1	0.0	457.5	70.3	0.0	21.5
					Totals:	365	3,236,000					

Results of linear regression:

Data Excluded: Chiller broke in mid-May 1995 for three weeks, June 10 electrical utility bill excluded from analysis.

```
WINTER LINEAR REGRESSION
base load   [kWh/day]                              8,603.05
weather factor   [kWh/HDD]                         -44.2555
CV(STD)                                               0.957
CV(RMSE) [%]                                           0.69

demand base load  [kW/mo]                            578.47
demand weather factor  [kW/HDD]                     -3.9649
demand CV(STD)                                        0.756
demand CV(RMSE) [%]                                    7.09

SUMMER LINEAR REGRESSION
base load   [kWh/day]                              7,678.43
weather factor   [kWh/CDD]                         229.4983
CV(STD)                                               0.975
CV(RMSE) [%]                                           2.17

demand base load  [kW/mo]                            413.37
demand weather factor  [kW/PKCDD]                    7.7157
demand CV(STD)                                        0.942
demand CV(RMSE) [%]                                    2.72
```

Natural Gas Meter

Weather Station: PITTSB Pittsburgh, Pennsylvania
Heating Balance Temperature: 60°F
Cooling Balance Temperature: 60°F

Reading Date	Days	Month	-- CONSUMPTION -- [Mcf]	Daily Consumpt. [Mcf]/day	HDD [°F]	CDD [°F]	Temp [°F]
1995-Sep-20	31	S	1,353	43.6	3.5	314.0	70.0
1995-Oct-20	30	W	1,435	47.8	77.5	77.5	60.0
1995-Nov-20	31	W	1,901	61.3	524.5	6.0	43.3
1995-Dec-20	30	W	2,198	73.3	795.5	0.0	33.5
1996-Jan-20	31	W	2,721	87.8	1,091.0	0.0	24.8
1996-Feb-20	31	W	2,721	87.8	1,088.0	0.0	24.9
1996-Mar-20	29	W	2,260	77.9	677.5	0.0	36.6
1996-Apr-20	31	W	2,218	71.5	533.5	18.5	43.4
1996-May-20	30	W	1,597	53.2	153.0	98.0	58.2
1996-Jun-20	31	S	1,448	46.7	18.5	260.5	67.8
1996-Jul-20	30	S	1,357	45.2	0.0	349.5	71.7
1996-Aug-20	31	S	1,445	46.6	0.0	294.5	69.5
Totals:	366		22,654				

Results of linear regression:

WINTER LINEAR REGRESSION	
base load [Mcf/day]	46.18
weather factor [Mcf/HDD]	1.1796
CV(STD)	0.941
CV(RMSE) [%]	2.72
SUMMER LINEAR REGRESSION	
base load [Mcf/day]	51.28
weather factor [Mcf/HDD]	-1.5785
CV(STD)	0.292
CV(RMSE) [%]	4.56

c. *Algorithm for Savings Calculations*

Electric Meter

Because linear regression results in good correlation of consumption with cooling degree-days, and demand with peak cooling degree-days, the following will be used for calculating the projected baseline

$$E_p = 7678.43 \times days_c + 229.4983 \times CDD_c\text{, for summer months}$$

$$E_p = 7516.34 \times days_c\text{, for winter months}$$

$$D_p = 413.37 + 7.7156 \times PKCDD_c\text{, for summer months}$$

$$D_p = 405.6\text{, for winter months}$$

The savings formulas are then

$$E_s = E_p - E_c$$

$$D_s = D_p - D_c$$

where

E_p = projected energy consumption
E_b = energy consumption in baseline month
E_c = current monthly energy consumption
E_s = monthly energy savings
$days_c$ = number of reading days in current month
CDD_c = number of cooling degree-days in current month
D_p = projected demand
D_c = current demand
D_s = monthly demand savings
$PKCDD_c$ = number of peak cooling degree-days in current month

Any estimated consumption and/or demand readings made by the utility company will need to be corrected before savings can be calculated. The savings calculation for May will assume that the chiller was operating correctly in the baseline period.

Natural Gas Meter

Because linear regression results in good correlation of consumption with heating degree-days, the following will be used for calculating the projected baseline:

$$E_p = 45.55 \times days_c\text{, for summer months}$$

$$E_p = 46.18 \times days_c + 1.1797 \times \mathrm{H}DD_c\text{, for winter months}$$

The savings formula is then

$$E_s = E_p - E_c$$

where

E_p = projected energy consumption
E_c = current monthly energy consumption
E_s = monthly energy savings
$days_c$ = number of reading days in current month
HDD_c = number of heating degree-days in current month

```
Electric Meter
NET DETERMINATION MEAN BIAS TEST

Consumption
 Original       Projected
                Base          Base  Energy   %
                Year          Year  Savings Energy
Month   [kWh]     [kWh]      [kWh]     Saved
Sep           261,500     265,476     3,976       1.52
Oct           237,500     244,008     6,508       2.74
Nov           246,000     240,523    -5,477      -2.23
Dec           215,000     225,490    10,490       4.88
Jan           221,000     225,490     4,490       2.03
Feb           231,000     233,007     2,007       0.87
Mar           237,000     225,490   -11,510      -4.86
Apr           263,000     254,335    -8,665      -3.29
May           205,500     205,500         0       0.00
Jun           337,500     345,446     7,946  2.35
Jul           336,500     330,529    -5,971 -1.77
Aug           354,500     350,705    -3,795 -1.07
Total       3,146,000   3,146,000         0  0.000000% <=========

Demand
 Original    Projected
                Base        Base  Energy   %
                Year        Year  Savings Energy
Month   [kW]  [kW]          [kW]      Saved
Sep           526       544.5         18.5        3.52
Oct           496       482.8        -13.2       -2.66
Nov           397       405.6          8.6        2.17
Dec           378       405.6         27.6        7.30
Jan           381       405.6         24.6        6.46
Feb           394       405.6         11.6        2.94
Mar           478       405.6        -72.4      -15.15
Apr           518       525.2          7.2        1.40
May           502       502.0          0.0        0.00
Jun           621       614.0         -7.0  -1.13
Jul           581       583.1          2.1   0.36
Aug           587       579.3         -7.7  -1.32
Total       5,859     5,858.9         -0.1        0.0017% <=========
```

```
Natural Gas Meter       NET DETERMINATION MEAN BIAS TEST

Buildings:            1   Main Hospital
Meters:               2   Main Natural Gas Meter

 Original       Projected
                Base          Base  Energy   %
                Year          Year  Savings Energy
Month   [Mcf]        [Mcf]   [Mcf]   Saved
Sep               1,353     1,412         59      4.37
Oct               1,435     1,477         42      2.91
Nov               1,901     2,050        149      7.86
Dec               2,198     2,324        126      5.73
Jan               2,721     2,719         -2     -0.09
Feb               2,721     2,715         -6     -0.22
Mar               2,260     2,138       -122     -5.38
Apr               2,218     2,061       -157     -7.08
May               1,597     1,566        -31     -1.95
Jun               1,448     1,412        -36     -2.48
Jul               1.357     1,367         10      0.71
Aug               1,445     1,412        -33     -2.27
                22,654     22,653         -1      0.0044% <=============
```

d. The measurement procedure.

Because the energy and demand values are taken from the measurements made by the utility company, no special measurement procedures will be necessary. Utility bills will be forwarded from the client for entry into a program that will calculate the energy use, demand, and cost savings and produce reports on a monthly basis. This monthly monitoring is expected to cost $1000 annually.

e. Quality control procedures.

Quality control will be monitored by one or more of the following:

- entering of meter readings and comparison of calculated consumption versus utility-provided consumption values,
- validation of billing demand from actual demand, kVA, or power factor and rate structures,
- comparison of actual energy and demand with expected values. This will help pinpoint poor estimates made by the utility company.

All baseline authorization, access to change data, record keeping, and corrections to estimated readings will follow internal ISO procedure and work instructions.

f. The savings reporting frequency and format.

Savings will be reported on a monthly basis and sample reports are shown below.

```
Electric Meter

ENERGY SAVINGS REPORTPeriod:             1998.10.01 to 1999.09.30
Consumption
                        Projected
                        Base                    Current                 %
    Savings Year                    Year                    Savings     EnergyUncertainty
    Month   [kWh]                   [kWh]                   [kWh]       Saved    %
Oct         10            241,838     187,000      54,838    22.68        5.45
Nov         11            235,523     180,000      55,172    23.46        5.20
Dec         12            240,523     172,000      68,523    28.49        4.98
Jan         13            225,490     188,000      37,490    16.63        4.78
Feb         14            225,490     165,500      59,990    26.60        4.61
Mar         15            233,007     201,000      32,007    13.74        4.45
Apr         16            244,008     222,000      22,008     9.02        4.31
May         17            286,236     233,000      53,236    18.60  4.18
Jun         18            339,929     274,500      65,429    19.25        4.06
Jul         19            361,167     290,000      71,167    19.70  3.95
Aug         20            327,545     278,500      49,045    14.97  3.85
Sep         21            277,725     232,000      45,725    16.46        3.76
Total                   3,238,129   2,623,500     614,629    18.98

Demand
                        Projected
                        Base                    Current                 %
   Savings  Year                    Year                    Savings     EnergyUncertainty
   Month    [kW]                    [kW]                    [kW]        Saved    %
Oct         10           486.7        444           43                   8.77  14.80
Nov         11           479.0        432           47        9.80        14.12
Dec         12           405.6        352           54                  13.21  13.51
Jan         13           405.6        313           93                  22.83  12.98
Feb         14           405.6        305          101       24.80        12.51
Mar         15           405.6        315           91       22.34        12.09
Apr         16           517.5        412          106   20.39            11.70
May         17           590.8        462          129                  21.80  11.35
Jun         18           621.7        509                     113       18.13  11.03
Jul         19           617.8        521           97       15.67        10.74
Aug         20           575.4        498           77       13.45        10.47
Sep         21           540.7        474           67       12.33        10.22
Total       6,052.0     5,037                   1,015                   16.77
```

Natural Gas Meter						
ENERGY SAVINGS REPORT						
Period:		1998.10.01 to 1999.09.30				
Savings Month		Projected Base Year [Mcf]	Current Year [Mcf]	% Savings [Mcf]	Energy Saved	Uncertainty %
Oct	10	1,518	1,104	414	27.28	7.83
Nov	11	1,962	1,499	463	23.62	5.20
Dec	12	1,943	1,487	456	23.48	4.98
Jan	13	2,671	2,137	534	20.01	4.78
Feb	14	2,256	1,901	355	15.74	4.61
Mar	15	2,318	1,820	498	21.50	4.45
Apr	16	1,896	1,451	445	23.46	4.31
May	17	1,518	1,179	339	22.31	4.18
Jun	18	1,412	1,098	314	22.24	4.06
Jul	19	1,367	1,032	335	24.48	3.95
Aug	20	1,412	996	416	29.46	3.85
Sep	21	1,412	1,054	358	25.36	3.76
Total		21,686	16,758	4,928	22.72	

The column "Uncertainty (to date) %" is taken from the following formula:

$$U = \frac{1.26 \times CVRMSE \times t}{F} \times \sqrt{\frac{n+2}{n \times m}}$$

For the natural gas meter, for month 14 of the savings:

$CVRMSE$ = 4.56%

t = 1 (from Table 5.1 with a confidence level of 68%)

n = 12 (number of points in regression model)

F = 25% (estimated annual savings)

m = 14

$$U = \frac{1.26 \times 4.56 \times 1 \times \sqrt{(12+2)}/(12 \times 14)}{25}$$

$$= 4.61\%$$

C2 Examples for Clause 6.2 Retrofit Isolation Approach

C2.1 Example Variable Inlet Vanes to VSD Retrofit Project Using Retrofit Isolation Approach

a. Compliance statement

This M&V plan is in compliance with ASHRAE 14 compliance path 5.3.2.3, "Retrofit Isolation," with maximum allowable uncertainty of 15% (compliance with ASHRAE 14 "Retrofit Isolation" requires savings uncertainty to be less than 50%).

b. Project summary

An office building located in San Luis Obispo, California, will retrofit 14 supply and return HVAC fans that currently have inlet guide vanes to control air flow with variable speed drives that will control the fan motor speed to control the air flow. The building typically operates seven days per week with reduced occupancy during evenings and weekend hours. In addition to offices, there are various labs, research areas, storage areas, lounge areas, and a health center that operate on different schedules. The project is being installed as part of a guaranteed savings performance contract with an ESCO.

This is not a VAV conversion. The building's HVAC system currently operates as a variable air volume system, and no chiller plant or boiler plant savings are expected from this retrofit. The VSDs will be controlled on the basis of maintaining downsteam static pressure that varies as different building zones call for more or less airflow. Project activities consist of disabling inlet vane dampers, linkages, and actuators and installing VSDs, relays, and power monitoring/communications equipment. No changes will be made to the building's HVAC system zone VAV boxes, downstream dampers, or controls.

Table C2.1-1 presents a summary of the building and estimated savings.

TABLE C2.1-1
VSD Project Summary

Square Footage of Building	Annual Building Energy Consumption	Projected Annual kWh Savings	Percent of Total Use
225,000	15,600,000	501,000	3%

c. Assumptions

This M&V plan was written with the following assumptions:

1. The office building plans no major building projects, such as building additions, or changes that would significantly alter the current building occupancy rate or schedule.
2. The ventilation operating schedule will not change because of this project.
3. The facility's existing energy management system (EMS) can be used as a part of the post-installation monitoring.
4. A relationship between a fan's pre-installation energy consumption and air flow rate can be obtained through short-term monitoring, which can be used to determine the fan's pre-installation energy consumption for any given air flow rate.
5. A relationship between a fan's post-installation energy consumption and air flow rate can be obtained through short-term monitoring, which can be used to determine the fan's air flow rate for any given energy consumption.
6. The EMS will call for the same percent air flow from the fans both pre- and post-retrofit to maintain the static pressure setpoints regardless of inlet vanes or VSDs controlling the air flow rate.
7. For the purposes of estimating energy savings, the fans were assumed to operate a total of 8,760 hours (see Table C2.1-8 for a description of typical operating hours excluding holidays).

d. M&V activities

The ESCO has monitored the air flow (CFM) and power consumption (kW) of the existing fan systems for a period sufficient to capture a full range of air flow rates from the fans and built a regression model for each fan system that relates the baseline kW to CFM. After the VSDs are installed, the inlet vanes removed, and the new system is commissioned, the ESCO will again monitor the CFM and kW of the fan systems for a period sufficient to capture a full range of air flow rates. A post-installation regression model will be built for each fan system relating kW to CFM. For the length of the program, the post-installation fan system kW and operating hours will be continuously monitored.

The baseline and post-installation monitoring techniques used are as defined in ASHRAE 14, Annex E, part 2 (fans), method #5: "Multiple Point Test through Short-Term Monitoring."

Energy savings will be calculated in a four-step process.

1. The post-installation continuous monitoring system will record the average motor kW draw for every 15-minute time interval.
2. The post-installation regression equation will be used to estimate the CFM for that average kW.
3. Using the CFM obtained from the post-installation regression, the baseline regression equation will be used to obtain the estimated baseline kW for that CFM.
4. Once the baseline and post-installation kW values are known, a subtraction of the post-installation kW from the baseline kW will yield the average kW savings for the 15-minute time period. Multiplying the kW savings by 0.25 hours (15 minutes in decimal form) will give the energy (kWh) savings for the 15-minute period.

The ESCO will make use of the office building's existing ACME energy management system (EMS) for recording VSD power consumption. Additionally, instantaneous, short-term, and continuous power-monitoring equipment will be used. Short-term air flow monitoring equipment will also be employed. See Clause E.2 for more information on the specific equipment that will be used.

For this project, the overall M&V approach includes the following components:

- *Inventory of Equipment.* Surveys have been conducted to document existing (baseline) motors and motor controls (e.g., motor starters and inlet vane dampers).
- *Metering Baseline Equipment.* Short-term metering has been conducted and observed by the building owner's representative on all baseline motors to develop the baseline regression model for power draw as a function of air flow rate.
- *Metering Post-Installation Equipment.* Short-term metering will be conducted and observed by the building owner's representative on all post-installation motors to develop a post-installation regression model for air flow rate as a function of power draw. To develop each fan system's post-installation model, the kW and CFM will be monitored at 15-minute intervals for a period long enough to capture the full range of expected air flow rates and at least a week, depending upon fan loading conditions.

For the continuous monitoring over the term of the program, the POWERSAV kW sensor/transmitter will be used to monitor the post-installation demand of the affected fan motors. The kW sensor/transmitters will be calibrated with the same kW meter used to establish the baseline and post-installation regression relationships. The EMS system will record the kW demand of each motor (output by the kW sensor/transmitter). Data will continuously be read and stored every 15 minutes throughout the term of the SPC program. The ESCO will download data from the EMS on a monthly basis and will take corrective action if the monitoring equipment is not operating properly. All data will be submitted to the building owner's representative in an electronic format for inspection and review.

e. Calculations and adjustments

Baseline Regressions for Fan Power Consumption

Regression relationships were developed relating each fan's power consumption to the corresponding air flow rate using a spreadsheet regression tool. The regression equations will be used to estimate the baseline power consumption once the vanes are disconnected and the fans' air flows are controlled by the VSDs. For all the fans, the regression analyses yielded equations with R^2 values of greater than 0.98, meaning the equations capture at least 98% of the power consumption characteristics of the fans. The t-statistic for the

TABLE C2.1-2
Baseline Power Consumption Regressions

Fan I.D.	Equation	R^2	SE
S-1	$y = 10.4030 + 10.5248x - 18.0789x^2 + 26.9252x^3$	0.9915	0.5688
S-2	$y = 10.3957 + 10.4487x - 19.0382x^2 + 28.2856x^3$	0.9959	0.4013
S-3	$y = 10.9191 +3.3867x + 14.9550x^3$	0.9943	0.4477
S-4	$y = 10.9291 + 3.6195x + 14.1278x^3$	0.9902	0.5689
S-5	$y = 14.4886 + 21.9351x^3$	0.9876	0.7847
S-6	$y = 10.5572 + 10.6577x - 20.4243x^2 + 29.4898x^3$	0.9929	0.5267
S-7	$y = 13.6589 + 2.9424x + 19.4597x^3$	0.9888	0.7729
R-1	$y = 5.9346 + 8.6009x^3$	0.9871	0.3141
R-2	$y = 5.1804 + 6.3106x - 13.0719x^2 + 16.6547x^3$	0.9948	0.2219
R-3	$y = 5.3273 + 4.4642x - 9.1618x^2 + 14.3863x^3$	0.9952	0.2133
R-4	$y = 4.9288 + 7.0136x - 12.5063x^2 + 15.4316x^3$	0.9916	0.2826
R-5	$y = 8.0309 + 2.2653x + 10.6592x^3$	0.9926	0.3598
R-6	$y = 5.7877 + 8.9539x^3$	0.9831	0.3745
R-7	$y = 7.887 + 6.1534x - 13.3275x^2 + 21.9334x^3$	0.9973	0.2459

where

y = Fan Motor Power (kW)

x = Percent of fan system maximum air flow rate (% CFM).

variables in the equations (CFM, CFM^2, and CFM^3) was used to check the relevance of the variables. In all the equations, the t-statistics were greater than 2.110, meaning there is a 95% confidence level that the variables are useful in predicting the power consumption of the fan. Table C2.1-2 contains the regression equations for each fan and the corresponding R^2 value and standard error of the equations.

Net Determination Bias

ASHRAE 14 requires that the net determination bias error be less than 0.005%. This minimizes computational uncertainty introduced by the algorithm employed. Computational methods in retrofit isolation include three steps

1. Development of the baseline model.
2. Filtering that may be applied to post-retrofit independent variable data.
3. Application of the possibly filtered post-retrofit independent variable data to the baseline model to determine the baseline energy or demand adjusted to post-retrofit conditions.

For this project, no filtering of the independent variable, %CFM, is to be performed, either in the baseline or post-installation period. Therefore, no computational uncertainties will be introduced to the savings calculation.

Post-Installation Regressions for Fan Power Consumption

Using the post-installation monitored data, regression relationships will be developed that will relate each fan's power consumption to the corresponding air flow rate. Cubic relationships between the dependent variable (power consumption) and the independent variable (percentage air flow) will be investigated and developed. Statistical t-testing of each relationship's coefficients will be performed, and only statistically significant coefficients will be used in the relationships. Coefficients will be considered significant if the t-statistic is greater than 2.0. Further, relationships will be developed that have coefficients of determination (R^2 values) greater than 0.96. For each relationship, the standard error will also be recorded.

It is not expected that other variables will have influence on each fan's power consumption, but if a satisfactory cubic relationship cannot be developed, other influencing variables will be investigated.

Post-Installation Calculation of Energy Savings

The calculations described below will be performed each year of the contract. The results will be reported in annual measurement and verification reports and will form the basis for verifying that the guaranteed savings were obtained.

Energy savings for each time interval (1/4 hour) will be calculated by determining the power reduction for that time interval and multiplying by the time interval, using the following equations:

$$kWh\ Savings \text{ (per 15-minute time interval)} = [0.25 \times [kW\ Savings \text{ in that time interval}]$$

$$kWh\ Savings_{annual} = Sum(kWh\ Savings \text{ for all time intervals in the year})$$

where

$kWh\ Savings_{annual}$ = annual energy savings [kWh]

$kW\ Savings$ = ($kW_{baseline} - kW_{post}$), the demand savings during a given metering time interval.

$kW_{baseline}$ = the kilowatt demand the baseline motor would have required if the VSD had not been installed. The baseline kW will be obtained from a motor's baseline power consumption regression equation. Air flow rate is used as an input to the regression equation.

kW_{post} = the kilowatt demand of the motor with the VSD during the post-installation time interval [kW] as recorded by the EMS.

Uncertainty Analysis

Energy savings for each fan will be reported with an accompanying uncertainty statement. The maximum allowable uncertainty for energy savings, for each fan is 50% at the 68% confidence interval. This M&V plan allows only 15% maximum uncertainty at the 68% confidence interval. Savings uncertainty will be determined using equation 5-7 in ASHRAE 14:

$$U = \frac{t}{F}\sqrt{\frac{CVRMSE^2}{m}\left[\frac{n}{n'}\left(1.6 + \frac{3.2}{n'}\right)\right] + U_s^2 + RE_{inst}^2} + t \times U_{iv}$$

where

t = student's *t*-statistic, tabulated in most statistics texts, for 68% confidence intervals, $t = 1$,

$F = \dfrac{kWh_{baseline} - kWh_{post}}{kWh_{baseline}}$ = fraction of energy saved,

$CVRMSE = \dfrac{SE_{regression}}{\overline{kW}_{regression}}$ = coefficient of variation of the baseline regression model,

$SE_{regression}$ = standard error of the regression model,

$\overline{kW}_{regression}$ = average kW of all measured kW used in the regression,

m = number of monitoring periods (1/4 hours) in the post-retrofit period,

n = number of data points in the baseline model

n' = number of independent observations (data points) in a total of *n* observations,

U_s = uncertainty due to sampling,

RE^2_{inst} = measurement error of non-billing energy meters or stored energy quantities,

U_{iv} = uncertainty generated in the baseline kW from the uncertainty in the independent variables (%CFM) measured in the post-installation period. U_{iv} is determined by the difference in baseline kW generated with the independent variables at their maximum values and the baseline kW generated with the independent variables at their minimum values.

For each regression,

m = $4 \times 24 \times 7 \times 52 = 34{,}944$ monitoring periods in a year

n = 21 data points in each baseline model

n' = 21 independent observations

U_s = 0, no sampling

RE^2_{inst} = 0, measurement uncertainty for kWbaseline allowed to be zero by ASHRAE 14 (5.2.11.2)

U_{iv} can only be determined in the post-installation period, as it is dependent on the post-installation regression relationship for each fan. The post-installation regression relationships will be used in an inverse manner: kW_{post} will be monitored by the EMCS, and each value will be used to estimate %CFM. The uncertainty in the post-installation regression relationship will cause uncertainty in the estimated %CFM. The maximum %CFM value (= %CFM + (Δ%CFM), and minimum %CFM value (= %CFM - (Δ%CFM), will be used in the baseline regression relationship to determine two values of $kW_{baseline}$ for each fan. The difference between these values is U_{iv}.

U_{iv} is approximated by the CVRMSE of the baseline model for purposes of estimating the overall savings uncertainty. The overall savings uncertainty of each fan and the total estimated savings uncertainty for the project are shown in Table C2.1-3.

Data for the fractional energy savings, F, CVRMSE, and resulting savings uncertainty for each fan are provided in Table C2.1-3.

TABLE C2.1-3
Individual Fan Data and Estimated Savings Uncertainty

Fan I.D.	F (%)	CVRMSE %	$U_{savings}$ (%)
S-1	30.9%	3.4%	3.5%
S-2	30.6%	2.4%	2.5%
S-3	31.3%	2.7%	2.8%
S-4	31.1%	3.5%	3.5%
S-5	31.1%	3.9%	4.0%
S-6	30.9%	3.2%	3.2%
S-7	31.9%	3.8%	3.9%
R-1	29.1%	3.8%	3.9%
R-2	29.9%	2.7%	2.8%
R-3	29.5%	2.6%	2.7%
R-4	30.6%	3.4%	3.5%
R-5	33.4%	3.0%	3.1%
R-6	28.5%	4.6%	4.7%
R-7	33.1%	2.0%	2.1%
Total Uncertainty*			3%

*. Total uncertainty percentage is the sum-in-quadrature of the individual fan savings absolute uncertainties divided by the sum of savings from each fan.

TABLE C2.1-4
Monitoring Approach

Objective of Monitoring	Time Period	Type of Monitoring / Duration	Type of Measurement	Monitoring Equipment
Estimate baseline kW - %CFM relationship	Baseline	Short-term metering of the full range of operating conditions	Instantaneous measures of 3-phase kW and corresponding air flow rate	True RMS meter, pitot probe and transmitter
Estimate post-installation kW - %CFM relationship and confirm EMS accuracy	Post-installation	Short-term metering of the full range of operating conditions	Instantaneous measures of 3-phase kW and corresponding air flow rate	True RMS meter and multimeter, pitot probe, and transmitter (same equipment used in baseline measurements)
Estimate post-installation kW; also verifies operating hours.	Continuous post-installation	Continuous monitoring (throughout performance period)	kW at 15-minute intervals	kW sensor and EMS calibrated with true RMS meter

f. Metering plan

Table C2.1-4 presents the monitoring approach the ESCO will use as the basis to estimate energy and demand savings associated with the VSD installation projects.

In addition to the metering, the status of the installed equipment (physical condition and continued operation) will be observed and changes will be reported in the measurement and verification reports. Annual calibration checks of the EMS and kW sensor/transmitters will be conducted at a range of operating points and reported to the building owner's representative at the end of each year of the contract.

The remainder of this clause addresses measurement and monitoring points, types of metering equipment, and metering equipment calibration.

The post-installation operating schedule will be confirmed by the data to be recorded by the EMS system.

Metering equipment will include true RMS meters, the ACME True RMS kW sensor/ transmitters, and the EMS system and air flow monitoring equipment. The ESCO will install the ITT POWERSAV kW sensor/transmitters to continuously monitor each motor's kW during the post-installation period. The kW sensor/transmitter will send output to the EMS, which will record the data. The specifications for the POWERSAV kW sensor/transmitter demonstrate that its accuracy and repeatability meet the requirement of ±2% of actual reading. A Jones True RMS wattmeter that meets the accuracy requirements will be used to record power consumption during the performance tests to establish the pre- and post-installation regression equations. The Jones will also be used to confirm and calibrate the EMS power readings at the time of the VSD installation and at the end of the first year of operation. The ESCO will use a Smith VOLU-probe, pitot airflow traverse probe, and an ACME differential pressure transmitter to record airflow rate during the pre- and post-installation performance testing.

Cut-sheets and specification of all the monitoring equipment are included with this M&V plan. Instantaneous measurements of motor power draw will be made using a ACME Model 40 true RMS meter with an accuracy at or greater than ± 2% of reading. The same ACME Model 40 meters will be used to make the instantaneous measurement for the motors before and after installation of the VSDs. Measurements of post-installation kW use will be recorded at 15-minute intervals by the site's EMS system.

All metering equipment will be calibrated at least once a year using National Institute of Standards and Technology traceable instrumentation.

g. Accuracy requirements

Accuracy requirements for all power monitoring devices are specified as being within ±2% of true reading. Air flow monitoring equipment will have an accuracy of ±5%. This is consistent with information provided in ASHRAE 14, Annex A.

Regression relationships between air flow rate CFM and motor kW developed for the baseline and post-installation motor power consumption will have an R^2 value of at least 80%, with absolute values for t-statistics of explanatory variables greater than 2.

h. Data gathering and quality control

The data will be collected using quality control procedures for checking the measurements for reasonableness.

The ESCO will provide documentation on the actual implementation of the metering plan, including specifics related to any change in the type of metering equipment, monitoring points, the monitoring schedule, and the data collection procedures. This information will be reported along with estimates and calculations of energy savings in the measurement and verification report.

i. Reports to be prepared

Following the installation and commissioning of the new VSDs and instrumentation, a post-installation report will be produced documenting that the equipment specified was installed and is functioning as expected. Yearly measurement and verification reports will be generated and submitted following completion of the year-long data collection activities. Savings estimates will be provided in spreadsheet form indicating monthly baseline, post-installation, and savings values. In addition to the reports, all monitoring data will be submitted in electronic format for review by the owner.

j. Schedule

Table C2.1-5 presents tasks and the schedule required to implement the measurement and verification plan.

k. Project budget

Table C2.1-6 below estimates the cost of the M&V activities for this project.

TABLE C2.1-5
Tasks for Implementing the M&V Plan

	Task	Responsible	Scheduled Completion
1.	Notify building owner's representative and take short-term measurements of baseline equipment KW and corresponding air flow rate	ESCO	8/98
2.	Accompany building owner's representative on pre-installation inspection	ESCO	10/98
3.	Give approval to proceed	Building owner's representative	12/98
4.	Complete installation of VSDs	ESCO	3/99
5.	Notify building owner's representative and take short-term post-installation measurements of equipment kW and corresponding air flow rates. Calibrate EMS kW meters with short-term monitoring equipment.	ESCO	3/99
6.	Submit post-installation report – including a sample data file from the EMS system and sample savings calculations	ESCO	3/99
7.	Accompany building owner's representative on post-installation inspection.	ESCO	4/99
8.	Building owner's representative approves the post-installation report.	Building owner's representative	4/99
9.	Submit first annual M&V report	ESCO	3/00

TABLE C2.1-6
Project M&V Costs

Tasks	Rate	Annual Hours	Total Cost
First Year			
Develop an implementation plan and coordinate schedule	$75	24	$1,800
Develop data collection protocol	$75	16	$1,200
Spot meter baseline motors/air flow	$75	64	$4,800
Data analysis	$75	40	$3,000
Post-installation spot metering of motor kW and air flow rate and calibrate EMS	$75	64	$4,800
Savings analysis	$75	24	$1,800
Subtotal (first year)		**232**	**$17,400**
Second through fifth year			
Post-installation data collection, per year	$75	48 x 5	$18,000
Data analysis and reporting, per year	$75	24 x 5	$9,000
Subtotal (2nd – 5th year)		**360**	**$27,000**
Equipment costs			$8,000
Grand total		**592**	**$52,400**

VSD retrofit cost = $230, 000
M&V cost = $52, 400
M&V cost as percent of project cost = 22.8%

l. Alternative M&V approaches

There are alternative M&V approaches if (a) the M&V budget for the approach described above is too expensive given the value of the project and the anticipated risk of achieving savings and/or (b) the air flow measurements are problematic. These include three options for determining the baseline that do not involve baseline or post-installation air flow measurements:

Observe secondary, non-CFM, independent factors (e.g., time of day, day of the week) to see if these correlate well with power consumption, without measuring CFM

Conduct baseline monitoring for a longer period of time and assume a conservative constant baseline

Use standard equations for vane, damper, and VSD-controlled fans to generate kW vs. CFM curves, and set the curves based on short-term kW monitoring results

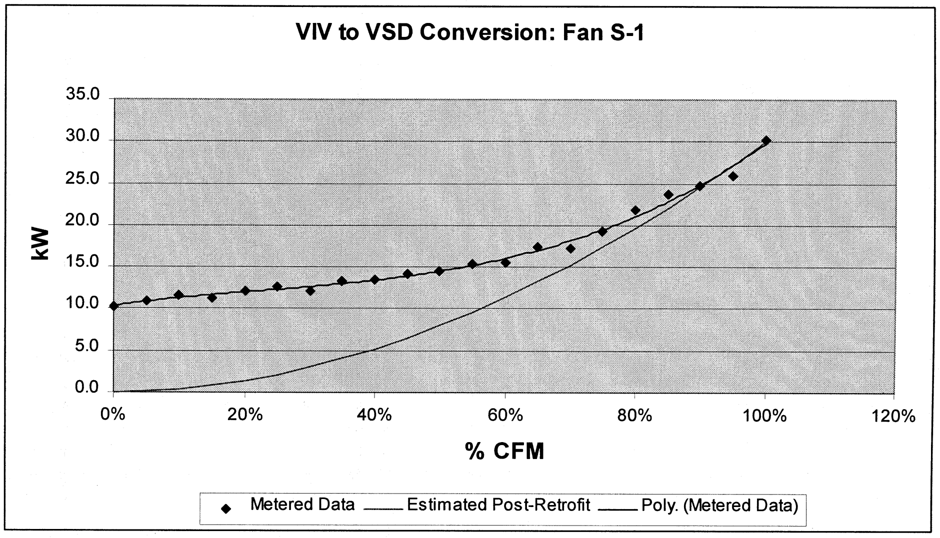


Figure C2.1-1 Sample baseline data with regression curve and estimated post-installation power consumption

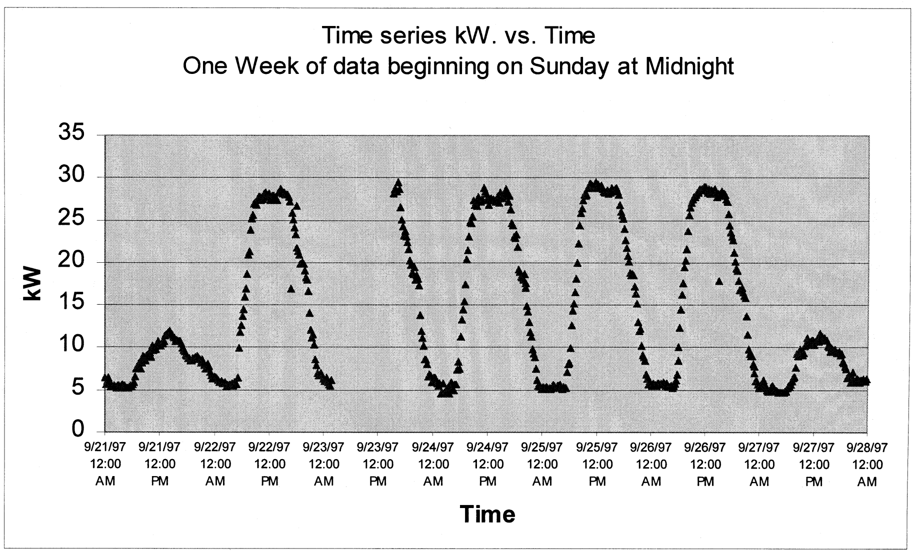


Figure C2.1-2 Fan power consumption following a daily pattern.

Secondary Factor Correlations

Power consumption of the fan motors may closely follow factors other than CFM. These may include time of day, day of the week, and/or outside air temperature. If a regression model can be built with satisfactory results (e.g., $R^2 > 0.8$), CFM will not need to be monitored. However, additional monitoring (seasonal) is needed to verify the correlation is valid the entire year. Figure C2.1-2 shows an example of baseline power consumption following a daily pattern.

Conservative Constant Baseline

If the baseline power draw is variable but stays within limited bounds, a conservative constant baseline may be assumed. This usually requires longer baseline metering to gain confidence in the upper and lower limits of the variation (e.g., seasonal monitoring). Note that this approach tends to result in a lower estimate of savings being validated; however, the M&V is easier and may be less costly. Figure C2.1-3 shows an example of a conservative constant baseline example.

Standard Equations for M&V

Standard accepted equations for fans with vanes, dampers, or VSDs may be used to generate flow vs. power consumption curves. The maximum power consumption of the curve is set using the fan's measured full-load power consumption (at the maximum CFM). Once the full-load reading is known, an estimate for the fan's kW can be made for any flow rate as a percent of the maximum CFM. Figure C2.1-4

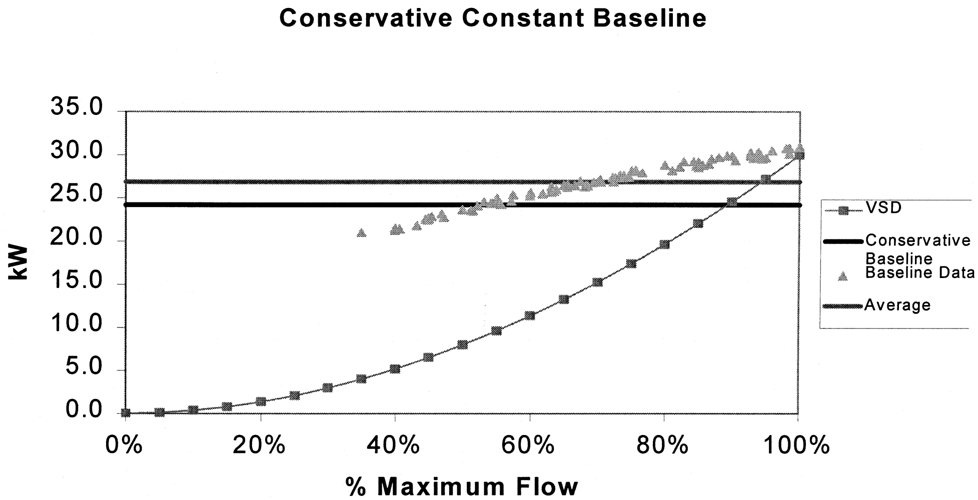
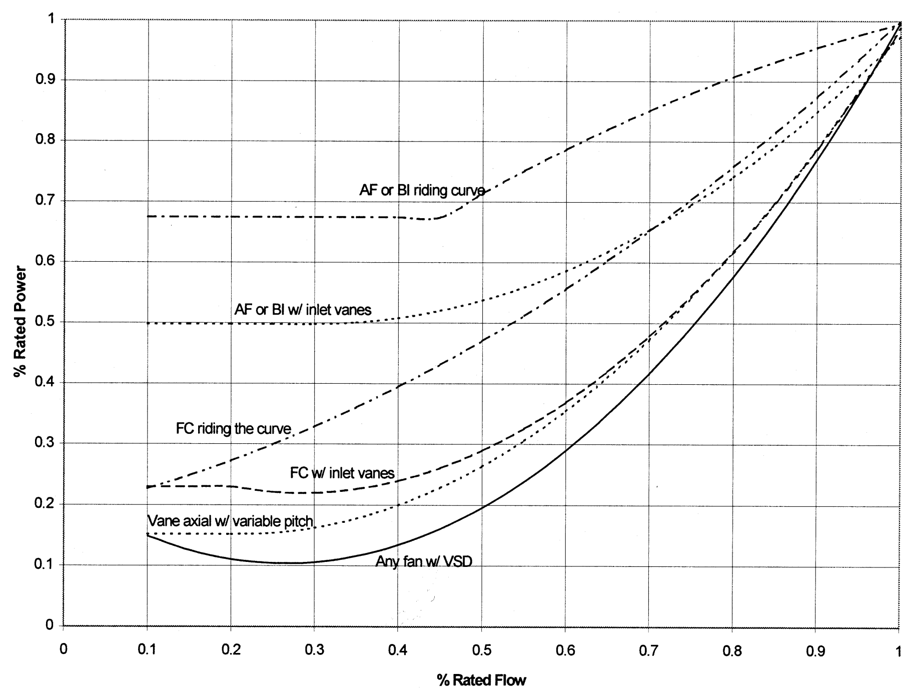


Figure C2.1-3 Assuming a constant baseline.



ASHRAE/IES Standard 90.1-1989 User's Manual - November 1992

Figure C2.1-4 Standard fan curve equations.

shows some graphs from standard equations for different fan system configurations.

To determine a savings estimate, the standard equations are used for the baseline. The steps are then:

1. Set the maximum kW for a baseline system curve at the measured full-load power consumption and likewise for the VSD system curve.
2. Then continuously measure post-installation kW. Use the VSD curve to establish the percent maximum CFM for any measured kW.
3. Look up the baseline kW from the baseline system curve for the same percent maximum CFM.
4. Subtract the baseline from the post-installation kW to determine the instantaneous power savings

Default Equipment Performance Curves

For variable volume systems, fan input power should be adjusted as a function of fan flow. This relationship is given by the following equation:

TABLE C2.1-7
Baseline Fan Measured Data

Fan	S-1	S-2	S-3	S-4	S-5	S-6	S-7	R-1	R-2	R-3	R-4	R-5	R-6	R-7
Air Flow	40 hp	40 hp	40 hp	40 hp	50 hp	40 hp	50 hp	20 hp	20 hp	20 hp	20 hp	30 hp	20 hp	30 hp
% of Maxi-mum	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW	kW
0%	10.3	10.3	10.1	10.3	13.4	10.8	13.6	5.3	5.2	5.4	5.0	7.8	5.0	7.9
5%	10.9	11.2	11.1	11.2	13.5	11.0	13.3	5.7	5.7	5.5	5.3	7.7	5.3	8.3
10%	11.7	10.8	11.7	11.3	14.2	11.5	13.9	5.4	5.4	5.5	5.4	8.4	5.5	8.2
15%	11.3	11.8	11.8	11.3	14.1	11.2	13.9	5.9	6.0	6.0	5.9	8.9	5.6	8.5
20%	12.1	12.2	11.6	12.2	15.4	12.1	14.5	6.1	6.1	6.2	5.9	9.1	5.9	8.9
25%	12.6	12.7	12.5	12.6	14.5	12.7	15.5	5.8	6.0	5.8	5.9	8.6	6.0	9.4
30%	12.1	12.5	12.6	12.5	14.8	12.7	15.0	6.5	6.4	6.3	6.3	9.4	6.0	8.8
35%	13.3	12.6	12.9	12.4	15.3	12.9	16.2	6.4	6.6	6.1	6.6	9.1	6.5	9.1
40%	13.5	13.3	13.2	13.6	16.0	13.9	15.7	6.6	6.6	6.6	6.5	9.4	6.5	9.8
45%	14.1	13.7	13.3	14.2	16.2	13.5	17.7	6.8	7.2	6.9	7.2	10.1	6.8	10.0
50%	14.5	14.3	14.8	14.9	18.1	14.0	17.3	7.3	7.0	7.1	7.3	10.8	7.2	10.5
55%	15.4	14.8	14.5	14.8	18.9	15.5	19.1	7.2	7.2	7.7	7.7	11.0	7.3	10.7
60%	15.5	16.1	16.3	16.6	20.3	16.3	20.1	8.2	8.1	7.6	7.7	11.3	8.2	11.6
65%	17.4	16.9	17.5	16.1	21.6	17.2	19.9	8.5	8.8	8.3	8.5	11.9	8.3	12.4
70%	17.2	18.8	18.2	18.6	22.5	17.8	21.3	8.9	8.7	9.0	8.7	13.1	9.4	12.9
75%	19.2	19.3	19.8	20.2	22.8	19.6	23.9	9.8	9.4	9.8	10.2	14.4	9.6	14.1
80%	21.9	21.3	20.9	20.9	26.2	21.9	27.1	10.9	10.5	9.9	10.8	15.3	10.3	15.4
85%	23.7	22.5	23.3	21.6	28.9	22.9	27.9	11.1	11.1	11.6	10.8	17.0	11.6	17.2
90%	24.7	24.5	25.3	23.9	29.0	23.7	29.6	12.1	12.3	12.4	11.9	18.2	12.9	19.0
95%	26.0	28.2	26.2	26.7	32.9	27.5	32.1	12.9	13.8	13.5	13.9	19.1	12.9	20.7
100%	30.3	29.8	29.6	29.5	36.6	31.0	37.6	14.3	15.1	15.1	14.9	20.7	14.3	22.3

TABLE C2.1-8
Estimated Distribution of Airflow by 10% Binned Operating Hours

Flow (%)	Annual Operating Hours
0	0
10	0
20	0
30	876
40	876
50	1,752
60	1,752
70	2,628
80	876
90	0
100	0
Total	8,760

$$P_{in}(CFM) = P_{out}(CFM) \times \left[A + B\left(\frac{CFM}{CFM_{max}}\right) + C\left(\frac{CFM}{CFM_{max}}\right)^2\right]$$

Fan Type—Control Type	A	B	C	Min Turndown (%cfm)	Min Input (%power)
AF or BI riding curve	0.227143	1.178929	–0.410714	45%	68%
AF or BI inlet valves	0.584345	–0.579167	0.970238	30%	48%
FC riding the curve	0.190667	0.31	0.5	10%	22%
FC inlet valves	0.339619	–0.848139	1.495671	20%	25%
Vane axial w/ variable pitch blades	0.212048	–0.569286	1.345238	20%	15%
Any VSD	0.219762	–0.874784	1.652597	10%	10%

C2.2 Example Chiller Replacement Project: Continuous Demand and Cooling Load Metering Using Retrofit Isolation Approach

a. Project summary

An owner of a 250,000 ft^2 office complex, located in San Jose, is participating in a guaranteed savings performance contract with an ESCO. The facility is cooled by a central chilled water plant with a 350-ton centrifugal chiller that is 10 years old. The owner of the building is planning to replace the existing chiller with a new, high efficiency, variable speed drive unit. No other changes are planned to the condenser or chilled water pumps or the cooling tower. The unit under consideration has been rated with an ARI nominal efficiency of 0.55 kW/ton. The efficiency of the existing chiller complied with ASHRAE 90.1 and has an ARI rated nominal efficiency of 0.748 kW/ton.

b. Assumptions

This M&V plan was written with the following assumptions:

1. The office building plans no major building projects, such as building additions, or changes that would significantly alter the current building occupancy rate or schedule.
2. The operating schedule will not change because of this project.
3. There is not adequate time to conduct pre-installation monitoring of the chiller due to the schedule for new chiller installation. Therefore, estimation of the baseline chiller electricity use will be established using the manufacturer's new condition ARI rating and standard operating curves established by the California Energy Commission in conjunction with monitored data. This assumes that the old chiller operates in a new and clean condition and that the manufacturer's data are accurate—as the chiller will probably have deteriorated during ten years of use, the savings determined by this M&V approach will tend to be conservative. Post-installation state points to be monitored include the chilled water supply and return temperature, chilled water flow, and condenser water supply temperature.
4. Post-installation energy use of the new chiller will be monitored.

Energy and demand savings are calculated as:

Post-installation chiller kW(h) $_{\text{(measured at time t)}}$

Minus

Pre-installation chiller kW(h) calculated $_{\text{(calculated at time t with load and temperatures of chilled water and condensor water)}}$

c. M&V activities

Since the baseline nominal efficiency for the chiller is defined by its ARI rating, no pre-installation metering will be required. M&V activities are composed of a post-installation inspection to verify the efficiency of the installed chiller, post-installation monitoring of chiller operating conditions, estimation of baseline energy use, and generation of M&V reports.

- *Pre-Installation Inspection:* Prior to installation of the new chiller, the existing chiller's nameplate data will be recorded and manufacturer's ARI rating obtained.
- *Post-Installation Inspection:* After the new chiller has been installed and commissioned, the ESCO and owner will conduct an inspection to verify that the chiller installed is consistent with what was proposed.
- *Post-Installation Monitoring:* Post-installation monitoring of chillier electricity use will be conducted for the entire M&V period. This monitoring will be accomplished using the existing building energy management system (EMS). The EMS will log and time stamp the data at 15-minute intervals, saving the data weekly to disk. In the event that there is a significant gap in the data due to a sensor failure, the process to replace the missing data with interpolated or averaged data will be clearly documented.
- *Estimation of Baseline Chiller Use:* Using the monitored, post-installation data described above, the baseline energy use will be computed. This estimation is a multi-step process that will compute the baseline energy use based on the chilled water supply temperature, condenser water return temperature, and estimated part-load ratio.*

d. Calculations and adjustments

The calculations described below will be performed for each year of the performance contract. The results will be reported in measurement and verification reports (MVR) and will form the basis for verifying guaranteed savings.

As previously mentioned, the proposed chiller is rated with an ARI nominal efficiency of 0.55 kW/ton, with a variable speed drive to provide unloading capability. From manufacturer's data, the baseline chiller has a nominal efficiency of 0.748 kW/ton, without a variable speed drive. To estimate the baseline load, a series of calculations will need to be carried out using the CEC-approved chiller characteristics.

After the new chiller is installed, the chiller's post-installation electricity use is measured. To compute the baseline energy use, the following calculations need to be carried out, for post-installation time "t":

- Calculate post-installation cooling load in tons
- Calculate chiller capacity
- Calculate the part-load ratio (PLR)
- Calculate the correction to chiller input power for the PLR
- Calculate the correction to chiller input power for chilled water supply and condenser water return temperatures
- Calculate the baseline electrical demand

The following notation is applicable to Equations 1 through 6 below:

$Tons_i$	Post-installation cooling output from chiller
CHWF	Chilled water flow (gallons per minute)
ECWT	Entering chilled water temperature (return temperature, (°F)
LCWT	Leaving chilled water temperature (supply temperature, (°F)

* The relationships used in the estimate of baseline chiller kW come from the March 1995 *Alternative Calculation Method (ACM) Approval Manual* from the California Energy Commission (publication P400-95-011).

TABLE C2.2-1
Proposed and Baseline Chiller Statistics

Chiller	Efficiency (kW/Ton)	Drive Type	Full-Load kW
Baseline	0.748	Constant	262
Proposed	0.550	Variable	193

CWT	Condenser water temperature (°F)
500	Conversion from GPM to pounds per hour (equation 1)
1	Btu per pound-degree Fahrenheit (equation 1)
12,000	conversion from Btu/h to tons (equation 1)
CAP_{nom}	Nominal capacity of chiller
Cap_i	Post-installation capacity of chiller
PLR_i	Post-installation part-load ratio
kW_{nom}	Nominal or full-load chiller demand (kW)
kW_i	Post-installation chiller demand (kW)
PLR_{Adj}	Adjustment to input power due to part load
$Temp_{Adj}$	Adjustment to input power due to chilled and condenser water temperatures

- Step 1 - Calculate cooling load. The cooling load will be computed based on the flow and temperature data collected with the EMS. Equation 1 below will be used to compute the tons of cooling currently being provided by the chiller.

$$Tons_i = \frac{(CHWF)(500)(ECWT - LCWT)(1)}{12,000} \qquad (1)$$

- Step 2 - Calculate post-installation capacity temperature correction. Capacity of any chiller is a function of the nominal capacity and the current chilled water and condenser water temperatures. The equation is bi-quadratic, with the coefficients defined by the CEC.

$$Capacity = Cap_{nom}(a + b(CHWT) + c(CHWT)^2 + d(CWT) + e(CWT)^2 + f(CHWT)(CWT)) \qquad (2)$$

where

a = –1.7420400
b = 0.0292920
c = –0.0000670
d = 0.0480540
e = –0.0002910
f = –0.0001060

- Step 3 - Calculate post-installation part-load ratio. The current part-load ratio is simply the ratio of current tons to current capacity.

$$PLR_i = \frac{Ton_i}{Cap_i} \qquad (3)$$

- Step 4 - Calculate the part-load adjustment to the nominal chiller kW. The result of this equation is a multiplier to be used with the chiller's nominal, full-load demand to estimate use at the given part load.

$$PLR_{adj} = a + b(PLR)_t + c(PLR)_t^2 \qquad (4)$$

where

a = 0.2229030
b = 0.3133870
c = 0.4637100

- Step 5 - Calculate the ambient adjustment to the nominal chiller kW. This adjustment factor accounts for the change in nominal chiller performance as a function of condenser and supply water temperatures.

$$Temp_{Adj} = a + b(CHWT) + c(CHWT)^2 + d(CWT) + e(CWT)^2 + f(CHWT)(CWT) \qquad (5)$$

where

a = 3.11750000
b = –0.10923600
c = 0.00138900
d = 0.00375000
e = 0.00015000
f = –0.00037500

- Step 6 - Calculate the current baseline chiller kW. Using the part-load and temperature adjustment factors, calculate the baseline chiller demand as the product of nominal chiller demand, PLR_{Adj} and $Temp_{Adj}$.

$$kW_i = (kW_{Nom})(PLR_{Adj})(Temp_{Adj}) \qquad (6)$$

Note that the above equation produces the average baseline kW for the interval associated with the data collected. Given that data are logged during a 15-minute time interval, the average kW estimated would need to be multiplied by 0.25 hours to convert to kWh.

Table C2.2-2 shows one day of chiller operation including illustrative data from the EMS, calculated adjustment factors, and estimates of baseline chiller demand. Note that the data from this example are assumed to be hourly average values calculated from the four 15-minute observations associated with each hour. The post-installation load data include the demand of the proposed chiller, condenser, and supply water temperatures. Calculated values include the post-installation capacity, part-load ratio (PLR), as well as the PLR and ambient adjustment factors. Based on the nominal baseline demand and the adjustment factors, the baseline kW for the given conditions is estimated. Finally, the last column in the table shows the hourly savings.

Note that savings could be calculated two other ways:

Instead of using manufacturer's data for the baseline chiller, measurements could have been made of the baseline chiller efficiency at part-load and/or full-load ratings.

The PLR and ambient adjustments could have not been made and the performance curves of the two chillers could have been assumed to be the same, for example, if a new chiller did not have a VSD on its compressor. In this situation savings would equal

TABLE C2.2-2
One Day Illustrative Data

Current Data					Calculated Values					
Hour of Day	New kW	Output (tons)	Condenser Temp. (°F)	Supply Temp. (°F)	Current Capacity (tons)	Part-Load Ratio	Part-Load Adjustment to EIR	Ambient Adjustment to EIR	Baseline Demand (kW)	Savings (kW)
1	117.30	240.5	79.7	44.6	363	0.663	0.635	0.927	154.11	36.81
2	114.69	235.1	79.6	44.6	363	0.65	0.62	0.93	150.56	35.87
3	115.02	236.1	79.5	44.6	363	0.65	0.62	0.93	150.97	35.95
4	114.62	235.2	79.5	44.6	363	0.65	0.62	0.93	150.42	35.80
5	114.25	234.4	79.5	44.6	363	0.65	0.62	0.93	149.92	35.67
6	113.47	232.7	79.5	44.6	363	0.64	0.61	0.93	148.88	35.40
7	115.85	238.0	79.5	44.6	363	0.66	0.63	0.93	152.11	36.26
8	125.51	258.4	79.6	44.8	364	0.71	0.68	0.92	164.27	38.76
9	131.66	270.5	79.7	44.9	364	0.74	0.71	0.92	171.96	40.30
10	131.95	270.3	80.0	44.9	364	0.74	0.71	0.93	172.55	40.60
11	135.19	276.8	80.0	44.9	364	0.76	0.73	0.93	176.94	41.75
12	136.27	278.4	80.2	44.9	364	0.77	0.73	0.93	178.57	42.31
13	140.65	287.0	80.2	45.0	364	0.79	0.76	0.93	183.93	43.29
14	138.67	282.4	80.4	44.9	363	0.78	0.75	0.93	181.93	43.26
15	140.25	286.1	80.2	45.0	364	0.79	0.76	0.93	183.35	43.10
16	137.13	279.9	80.2	44.9	364	0.77	0.74	0.93	179.65	42.52
17	140.37	287.2	79.9	45.0	364	0.79	0.76	0.92	183.28	42.92
18	136.55	279.6	80.0	44.9	364	0.77	0.74	0.93	178.87	42.32
19	134.40	275.4	79.9	44.9	364	0.76	0.73	0.92	175.77	41.37
20	132.92	273.2	79.7	44.9	364	0.75	0.72	0.92	173.71	40.79
21	130.55	268.9	79.5	44.8	364	0.74	0.71	0.92	170.88	40.32
22	130.05	267.9	79.5	44.8	364	0.74	0.71	0.92	170.22	40.18
23	123.08	252.9	79.7	44.7	363	0.70	0.67	0.93	161.47	38.40
24	113.93	233.3	79.6	44.6	363	0.64	0.62	0.93	149.45	35.52

Chiller Data:

Chiller	Nominal kW	Nominal tons	Nominal kW/ton
Baseline	262	350	0.748
New	193	350	0.55

Example Baseline kW Calculation (Hour 1):

$kW(1) = (kW_{nom})(PLR_{Adj})(Temp_{Adj})$
$kW(1) = (262\ kW)(0.635)(0.927)$
$kW(1) = 154$

$$kW(h)_{t,\ post\text{-}installation}$$

minus

$$[kW(h)_{t,\ post\text{-}installation} \times (kW_{baseline\ chiller,\ nominal} / kW_{new\ chiller,\ nominal})]$$

Post-Installation Calculation of Energy (and Average Demand) Savings

The calculations described below will be performed each year of the contract. The results will be reported in the measurement and verification report (MVR) and will form the basis of payments.

Energy savings for each time interval (hour) will be calculated by determining the power reduction for that time interval and multiplying by the time interval, using the following equations:

$$kWh\ Savings = kW\ Savings$$

(This is true since the time interval is one hour)

$$kWh\ Savings_{annual} = Sum(kWh\ Savings\ for\ all\ time\ intervals\ in\ the\ year)$$

where

$kWh\ Savings_{annual}$ = annual energy savings [kWh].

$kW\ Savings$ = $(kW_{baseline} - kW_{post})$, the demand savings during a given metering time interval.

$kW_{baseline}$ = the kilowatt demand the baseline chiller would have required if the new chiller had not been installed, as calculated by the procedure presented above.

kW_{post} = the kilowatt demand of the new chiller during the post-installation time interval [kW] as recorded by the EMS.

e. Metering plan

Metering of all plant parameters will be accomplished using the energy management system. Parameters to be monitored are the chiller demand, chilled water flow, condenser water temperature, and chilled water supply and return temperatures.

Chiller Demand: The chiller demand will be monitored using solid core current transducers installed at the time of chiller installation. These transducers will be installed on breakers 1, 3, and 5 (the A, B, and C phases) of switchgear SW-1. Calibration of these sensors will be accomplished using an ACME true RMS kW meter. Calibration of this parameter will be carried out once per year. Data will be recorded at a 15-minute interval.

Chilled Water Flow: Chilled water flow will also be monitored through the EMS. At the time of chiller installation, an ACME inline flow meter will be installed in the secondary chiller loop, between the chiller and the secondary pump. This flow meter is guaranteed by the manufacturer to have an accuracy of ±5%. This calibration will be verified using an ultrasonic flow meter. The verification of calibration will be conducted at the time of installation. The COP of the chiller will be continuously monitored to assist in identification of sensors that have fallen out of calibration.

Condenser and Chilled Water Temperatures: Water temperature sensors will be the insertion type, installed in new thermowells for both the condenser and supply water temperatures. The sensors used will be ACME two-wire, 1,000 OHM platinum RTDs paired with a 4-20 mA transmitter. The combined unit(s) will have an operating range of 20-120°F with an accuracy of ±0.50°F. A field check of calibration will be conducted using the analog thermometers installed in the supply and condenser water lines.

f. Accuracy requirements

In addition to the calibration and testing procedures outlined above, all components will be comprehensively tested and evaluated once each contract year. Also, the EMS will continuously monitor the calculated kW/ton of the new chiller and issue a warning when this value moves outside of a reasonable range (0.40 - 1.25 kW/ton).

g. Data gathering and quality control

The data will be collected using quality control procedures for checking the measurements for reasonableness. Any and all missing intervals will be replaced either by interpolation or use of average values.

h. Reports to be prepared

Following the installation and commissioning of the new chiller and instrumentation, a post-installation report will be produced documenting that the equipment specified was installed and is functioning as expected. Yearly measurement and verification reports will be generated and submitted following completion of the year-long data collection activities. Savings estimates will be provided in spreadsheet form, following the template provided in Table C2.2-2. In addition to the reports, all monitoring data will be submitted in electronic format for review by the owner.

i. Schedule

Table C2.2-3 presents tasks and the schedule required to implement the M&V plan.

j. Project budget

Table C2.2-4 estimates the cost of the M&V activities for this project.

TABLE C2.2-3
Tasks for Implementing the M&V Plan

Task	Responsible	Scheduled Completion
1. Approval of project	Owner	3/98
2. Install and commission new chiller	ESCO	7/98
3. Calibrate sensors and begin monitoring activities	ESCO	7/98
4. Develop post-installation report	ESCO	9/98
5. Conduct post-installation inspection	Owner	9/98
6. Complete first year M&V data collection	ESCO	9/99
7. Submit first year M&V report including all logger data in electronic format	ESCO	10/99

TABLE C2.2-4
Project M&V Costs

Tasks	Rate	Hours	Total Cost
Develop an implementation plan and coordinate schedule	$100	50	$5,000
Install and calibrate sensors	$75	40	$3,000
Post-installation report	$100	40	$4,000
Bi-monthly downloads and data validation, troubleshooting (five years)	$75	30 * 8	$18,000
Savings analysis and report generation (once every five years)	$100	40 * 5	$20,000
Instrumentation costs			$6,000
Grand total		810	$56,000

Chiller retrofit cost = $250,000
M&V cost = $56,000
M&V cost as percent of project cost = 22.4%

(This informative annex is not part of ASHRAE Guideline 14 but is provided for informational purposes only.)

ANNEX D: REGRESSION TECHNIQUES

D1 Eliminating Net Bias Error Due to Data Length Variation

Linear regression is the process of finding a "best fit" straight-line equation between a dependant variable and one or more independent variables. It assumes that variations (residuals) from the straight line are random and normally distributed. Then the best fit is one that minimizes the sum of the squares of the residuals. The conventional method of performing linear regression is called "ordinary least squares." It proceeds by minimizing the sum of the squares of the deviation of the actual values from those predicted by the straight line.

Assume the following actual data:

TABLE D-1

N	Billing Month	Days	HDD65	kWh
1	Jan	33	544	1426
2	Feb	27	672	1552
3	Mar	35	290	830
4	Apr	30	134	609
5	May	26	8	243
6	Jun	30	0	202
7	Jul	33	0	262
8	Aug	31	0	400
9	Sep	27	0	278
10	Oct	34	21	452
11	Nov	30	375	1112
12	Dec	26	716	1694
13	Jan	38	781	1884
14	Feb	29	617	1563
15	Mar	31	499	1230
Total:		460	4657	13737

It is a common error to throw all the variables into a regression analysis. In this case, the error would be to use the following equation as the model:

$$\text{kWh} = \alpha_0 + \alpha_1 \cdot Days + \alpha_2 \cdot HDD65 \qquad \text{(D-1)}$$

where α_0, α_1, and α_2 are unknown. This is erroneous because it implies a physical basis for a constant kWh use per data point (billing month), α_0, in addition to the use per day α_1 and use per degree-day α_2.

By dividing both kWh and base 65°F degree-days by the days in the meter-reading period, we can create two new variables, kWh per day and degree-days per day. By reference to physical reality, we know that the relationship is approximately linear. The following equation is the model:

$$kWh_d = \alpha_0 + \alpha_1 \cdot HDD65_d \qquad \text{(D-2)}$$

where the subscript d indicates daily averages, and α_0 and α_1 are the unknown use per day and use per degree-day. An ordinary least squares regression of kWh per day against degree-days per day will yield $\alpha_0 = 9.843875$ and $\alpha_1 = 1.979776$. However, the ordinary least squares technique is a simplification of a more general case, when all data points are equally weighted. In this example, some data points cover longer time periods than others. This means they should carry more weight. The equal weighting assumption results in the regression results being slightly off from the original data as shown below.

TABLE D-2

Billing Month	Days	Hdd65/day	Predicted kWh/day	Predicted kWh
Jan	33	16.48	42.48	1402
Feb	27	24.89	59.12	1596
Mar	35	8.29	26.25	919
Apr	30	4.47	18.69	561
May	26	0.31	10.45	272
Jun	30	0.00	9.84	295
Jul	33	0.00	9.84	325
Aug	31	0.00	9.84	305
Sep	27	0.00	9.84	266
Oct	34	0.62	11.07	376
Nov	30	12.50	34.59	1038
Dec	26	27.54	64.36	1673
Jan	38	20.55	50.53	1920
Feb	29	21.28	51.97	1507
Mar	31	16.10	41.71	1293
Total:				13748

Note that the regressed equation predicts total use over the period of 13748 kWh, while the actual total use was 13737 kWh. While this difference is small, it would grow as the data lengths varied more or as the actual data had more variation from a straight line. In addition, the difference means that the model fails the net bias test required by clause 6.1 of ASHRAE Guideline 14.

The solution is to weight each data point by the length of the time period from that point. Most standard statistical packages can perform weighted regressions. If only a spreadsheet program is available, the same result can be obtained by including each point as many times as the length of data covered. In this example, that would mean 33 points from observation number 1, 27 from observation number 2, etc.

An alternative is to simply perform the calculations. For a single independent variable such as this example,

$$\alpha_0 = \frac{(\sum WY \cdot \sum WX^2) - (\sum WX \cdot \sum WXY)}{(\sum W \cdot \sum WX^2) - (\sum WX)^2} \qquad \text{(D-3)}$$

$$\alpha_1 = \frac{(\sum W \cdot \sum WXY) - (\sum WY \cdot \sum WX)}{(\sum W \cdot \sum WX^2) - (\sum WX)^2} \tag{D-4}$$

Using equations 3 and 4 yields $\alpha_0 = 9.854235$ and $\alpha_1 = 1.976391$. Recalculating the predicted values gives the results below with no net bias. Note that using the number of days as weights, the quantity *WY* is billing period kWh and *WX* is billing period degree-days.

TABLE D-3

Billing Month	Days	Hdd65/day	Predicted kWh/day	Predicted kWh
Jan	33	16.48	42.43	1400
Feb	27	24.89	59.04	1594
Mar	35	8.29	26.23	918
Apr	30	4.47	18.68	560
May	26	0.31	10.46	272
Jun	30	0.00	9.85	296
Jul	33	0.00	9.85	325
Aug	31	0.00	9.85	305
Sep	27	0.00	9.85	266
Oct	34	0.62	11.07	377
Nov	30	12.50	34.56	1037
Dec	26	27.54	64.28	1671
Jan	38	20.55	50.47	1918
Feb	29	21.28	51.90	1505
Mar	31	16.10	41.67	1292
Total:				13737

Note that if all weights, *W*, are equal, then we get the equations for ordinary least squares:

$$\alpha_0 = \frac{(\sum Y \cdot \sum X^2) - (\sum X \cdot \sum XY)}{(N \cdot \sum X^2) - (\sum X)^2} \tag{D-5}$$

$$\alpha_1 = \frac{(N \cdot \sum XY) - (\sum Y \cdot \sum X)}{(N \cdot \sum X^2) - (\sum X)^2} \tag{D-6}$$

where *N* equals the number of observations.

D2 Multiple Independent Variables

There are several reasons to be extremely cautious in deciding to use multiple independent variables. The use of multiple independent variables in general decreases the usefulness of the data by one data point per additional independent variable, and the standard errors of the coefficients will show this. The "t-statistic" is the value of the coefficient divided by its standard error. A t-statistic of 2 is often used to decide whether an independent variable should be included. It is important to realize that a t-statistic of 2 means only that the coefficient has a 95% chance of being greater than zero; that is, there is a 5% chance we even have the sign wrong.

The number of independent variables can be reduced by first examining the physical parameters, then including only those that are independent and have physical causality. A clear benefit may be had by separating the data into different regimes of behavior, for example, heating season and cooling season. These could be modeled separately as shown later in this appendix.

Both standard statistical packages and spreadsheets can be used to perform weighted least square regressions with multiple independent variables. A set of "normal equations" for a least squares regression can be derived by expressing the sum of the weighted squares of the difference between the dependant variable and the predicted dependant variable in terms of the coefficients. Setting the partial derivatives with respect to each coefficient equal to zero will solve for the minimum sum of the weighted squares. This results in as many simultaneous equations as there are unknown coefficients. "When more than two parameters are involved, the problem requires the solution of *m* linear equations in *m* unknowns, with $m > 2$. The computational aspects of this problem are discussed in textbooks on algebra and need not detain us here. It is true that the normal equations have a symmetry that makes it possible to use special methods of solution, but the widespread use of high-speed computers has tended to relegate this problem to the field of programming " (Mandel 1964, p. 140). Mandel goes on to refer the interested reader to Anderson and Bancroft (1952), Bennett and Franklin (1954), Deming (1943), and Hald (1952).

D3 Data Requirements

At least 12 months of monthly pre-retrofit data are required to establish a baseline energy use (Fels 1986). Several years of monthly pre-retrofit data are preferred. In addition, any change of usage of the facility needs to be noted since this can significantly impact energy use.

D4 Energy Use Baseline Development with a Regression Model

An analysis must be conducted on the empirical behavior of the building as it relates to one or more driving forces or parameters. This approach is referred to as system identification, parameter identification, or inverse modeling. In the inverse modeling approach, one assumes certain characteristics about the building or system being studied and then attempts to identify the important parameters through the use of a statistical analysis (Rabl 1988; Rabl and Rialhe 1992). It is important to realize that the type of HVAC system will influence the model chosen. A system with reheat will show a different characteristic from one without it; the presence of heat recovery or an economizer cycle will also affect the model selection.

Several methods can be used to develop an energy use baseline.

The simplest form of an inverse model is a steady-state inverse model of a building's energy use. The simplest steady-state inverse model can be calculated by statistically regressing monthly utility energy use data against average billing period temperatures.

The most accurate methods use sophisticated change-point statistical procedures that simultaneously solve for several parameters, including a weather-independent base-level parameter, one or more weather-dependent parameters, and the point or points at which the model switches from weather-dependent to non-weather-dependent behavior. In its simplest form, the 65°F (18.3°C) degree-day model is a change-point model that has a fixed change point at 65°F. Examples include the three- and five-parameter Princeton Scorekeeping Method - PRISM (e.g., where the three parameters include weather-independent base-level use, change-point temperature, and a slope of the line fitted to the points above or below the change-point) (Fels 1986) and a four-parameter model (4P) developed by Ruch and Claridge (1991) (e.g., where the four parameters include a change-point, a slope above the change point, a slope below the change point, and the energy use associated with the change- point).

The one-parameter or constant model is frequently appropriate for electricity use in buildings that are on district heating and cooling systems.

The two-parameter cooling model is typically appropriate for modeling the cooling consumption of a building without an economizer and with a constant volume terminal reheat system or with a dual-duct constant volume system.

The four-parameter heating model is typically applicable to heating usage in buildings with a number of common VAV systems.

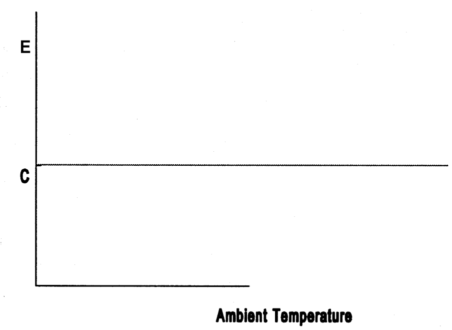


Figure D-1a Simple one-parameter model.

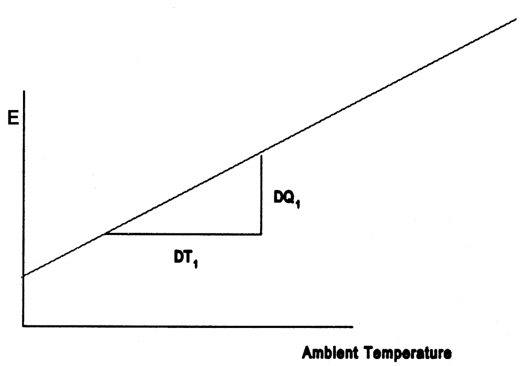


Figure D-1b Two-parameter cooling model.

The four-parameter cooling model is typically applicable to cooling usage in buildings with a number of common VAV systems.

Figures D-1a through D-1g show several types of steady-state, single-variable inverse models.

Figure D-1a shows a simple one-parameter, or constant model, and the equation gives the equivalent notation for calculating the constant energy use using this model.

$$E = C \tag{D-7}$$

Figure D-1b shows a steady-state two-parameter model where Bo is the y-axis intercept and B is the slope of the regression line for positive values of *T*, where *T* represents the ambient air temperature and the + means only use positive values.

$$E = C + B(T)_{+} \tag{D-8}$$

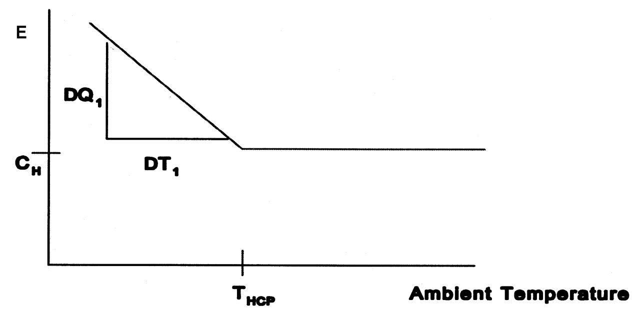


Figure D-1c Steady-state three-parameter heating model.

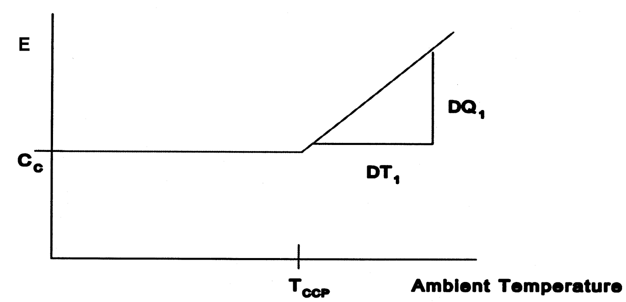


Figure D-1d Steady-state three-parameter cooling model.

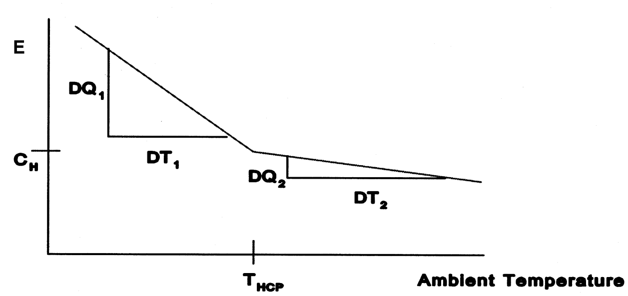


Figure D-1e Steady-state four-parameter heating model.

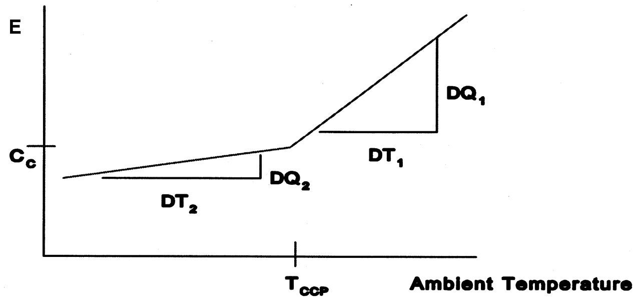


Figure D-1f Steady-state four-parameter cooling model.

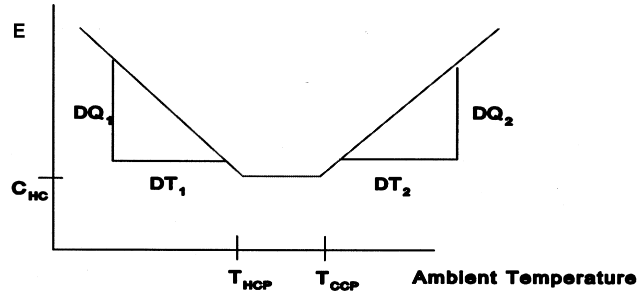


Figure D-1g Steady-state five-parameter heating/cooling model.

Figure D-1c shows a commonly used three-parameter, change-point model applied to heating. It is also known as a "variable-based degree-day model." This is typical of natural gas energy use in a single-family residence that utilizes gas for space heating and domestic water heating. In the expression that is given for the three-parameter model, C_H represents the heating baseline energy use and B_H is the slope of the regression line for values of ambient temperature less than the change-point T_{CP}. In this type of notation the subscript (+) indicates that only positive values of the parenthetical expression are considered.

$$E = C_H + B_H(T_{HCP} - T)_+ \qquad \text{(D-9)}$$

Figure D-1d shows a three-parameter model for cooling energy use, and the equation gives the appropriate expression for analyzing cooling energy use with a three-parameter model.

$$E = C_C + B_C(T - T_{CCP})_+ \qquad \text{(D-10)}$$

Figure D-1e illustrates a four-parameter model for heating. The following equations are the calculations for heating energy use using a four-parameter model. In a four-parameter model C_H represents the baseline energy exactly at the change-point T_{HCP}. B_{H1} and B_{H2} are the upper and lower region regression slopes for ambient air temperature above and below the heating change point T_{HCP}.

$$E = C_H + B_{H1}(T_{HCP} - T)_+ \qquad \text{if } T < T_{CCP} \qquad \text{(D-11)}$$

$$E = C_H + B_{H2}(T_{HCP} - T)_+ \qquad \text{if } T > T_{CCP} \qquad \text{(D-12)}$$

Figure D-1f illustrates a four-parameter model for cooling. The following equations are the calculations for cooling energy use using a four-parameter model. In a four-parameter model C_C represents the baseline energy exactly at the change-point T_{CCP}. B_{C1} and B_{C2} are the upper and lower region regression slopes for ambient air temperature above and below the cooling change point T_{CCP}.

$$E = C_C + B_{C1}(T - T_{CCP})_+ \qquad \text{if } T > T_{CCP} \qquad \text{(D-13)}$$

$$E = C_C + B_{C2}(T - T_{CCP})_+ \qquad \text{if } T < T_{CCP} \qquad \text{(D-14)}$$

The following equations give the expressions for calculating a five-parameter model where there are separate change-points for heating and cooling energy use as might be expected in an all-electric heat pump building for cases where the change point $B_3 < B_4$. For cases where there is simultaneous heating and cooling (i.e., $B_3 > B_4$) the base level B_o will be artificially high and submetering is recommended to differentiate between heating and cooling.

$$E = C_{HC} + B_H(T_{HCP} - T)_+ \qquad \text{if } T < T_{HCP} \qquad \text{(D-15)}$$

$$E = C_{HC} \qquad \text{if } T_{HCP} < T < T_{CCP} \qquad \text{(D-16)}$$

$$E = C_{HC} + B_C(T - T_{CCP})_+ \qquad \text{if } T > T_{CCP} \qquad \text{(D-17)}$$

There are several advantages of these steady-state linear and change-point linear inverse models, including the following.

1. The application can be automated and applied to large numbers of buildings where monthly utility billing data and average daily temperatures are available, and
2. it has been shown that linear and change-point linear models have physical significance to the actual heat loss/gain mechanisms that govern the energy use in most buildings (Bushnell 1978; Fels 1986; Rabl and Riahle 1992; Claridge et al. 1992; Rabl 1988).

The disadvantages of the steady-state inverse monthly models include an insensitivity to dynamic effects (e.g., thermal mass), insensitivity to variables other than temperature (e.g., humidity and solar), and inappropriateness for certain building types, for example, building that have strong on/off schedule dependent loads or buildings that display multiple change-points. In such cases alternative models will need to be developed, such as hourly or daily models.

All of the change-point models presented above are limited to weather-sensitive energy use. All can be extended to energy use that correlates with other variables, such as average daily meals served in a restaurant, average daily output of an industrial plant, etc. To correlate with such variables, each model above would receive one or more additional terms reflecting the non-weather-sensitive use. For example, extending the five-parameter model in equation 6.1.8 to an industrial facility with a cafeteria and a manufacturing plant might yield:

$$E = C + B_H(T_{\Delta H} - T)_+ + B_C(T - T_{\Delta C})_+ + B_M(M - M_\Delta)_+ + B_W(W - W_\Delta)_+$$

where M represents meals served per day, W represents widgets produced per day, B_M and B_W represent the marginal energy use per additional daily meal served or widget produced, and M_Δ, W_Δ, indicate a minimum floor of daily meals or daily production output below which energy use is not affected.

D5 Regression Model Selection

In general one would like a model selection procedure that is simple to apply and produces consistent, repeatable results. Several selection procedures have been recommended to select the best regression model. In general these procedures calculate several regression models and select the best model depending on the goodness of fit as measured by the R^2, coefficient of variation of the normalized annual consumption (i.e., CV(NAC)) or coefficient of variation of the root mean squared error (i.e., CV(RMSE). Additional information concerning these selection procedures can be found in Reynolds et al. (1990) and in Kissock (1993). Public domain software can be obtained from Princeton University (Fels et al. 1996) and from Texas A&M University (Kissock et al. 1994). Spreadsheet procedures have also been developed for accomplishing this in work done for Oak Ridge National Laboratory. Equations for determining the R^2, RMSE, and MBE are provided in Annex B.

In certain types of buildings, such as school buildings, where there is a significant difference between the building's energy use during the school year and non-school year, separate regression models may need to be developed for the different usage periods (Landman and Haberl 1996).

D6 Models Based on Measured Indoor Temperature

If thermostat setpoints change (e.g., weekend setback, seasonal setpoint changes, or other occupant/operator override) or the HVAC system does not maintain good temperature control, a changepoint model may not be adequate. If this is the case and energy use is strongly temperature dependent, it will be necessary to measure temperature (and possibly humidity as well) in the conditioned space(s). There may be other, more pressing reasons to monitor these conditions. For example, the project may call for an improved level of service as well as energy savings. (Bushnell 1978; Sonderreger)

D7 References

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Sonderegger, R. PhD dissertation or ASHRAE derivative(s)

(This normative annex is part of ASHRAE Guideline 14 and is required for its use.)

ANNEX E: RETROFIT ISOLATION APPROACH TECHNIQUES

E1 Retrofit Isolation Approach for Pumps

Pumping systems in building HVAC applications use different types and numbers of pumps, various control strategies, and several types of piping layouts. Pump electric power demand variation with heating or cooling loads depends on the system design and control method used. Building hydronic systems and their control typically fall into three categories:

Constant Speed and Constant Volume: Constant volume pumping systems use three-way valves and bypass loops at the end-use or at the pump. As the load varies in the system, pump pressure and flow are held relatively constant, and the pump input power remains nearly constant. Pump motor speed is constant.

Constant Speed and Variable Volume: Variable pumping systems use two-way control valves to modulate flow to the end-use as required. In constant speed, variable volume pumping systems, the flow varies along the pump curve as the system pressure drop changes in response to the load. In some cases, a bypass valve may be modulated if system differential pressure becomes too large.

Variable Speed and Variable Volume: Like the constant speed, variable volume system, flow to the zone loads is typically modulated using two-way control valves. However, in variable speed, variable volume pumping systems, a static pressure controller is used to adjust pump speed to match the flow load requirements.

In order to apply to a wide variety of pumping systems, the in-situ testing guidelines contain six different methods. The preferred method is determined by the user based upon the system type and control and the desired level of uncertainty, cost, and degree of intrusion. The first two methods involve testing at a single operating point. The third and fourth procedures involve testing at multiple operating points under imposed system loading. The fifth method also involves multiple operating points, in this case obtained through short-term monitoring of the system without imposed loading. The final procedure operates the pump with the fluid flow path completely blocked. While this procedure is not useful for generating a power versus load relationship, it can be used to confirm manufacturer's data or to identify pump impeller diameter.

Test methods have been developed to apply to the typical pumping systems described above, as outlined in Table E1-1. Different methods can be used for each type of pumping system depending on the available resources and possible degree of intrusion on operation. The following paragraphs describe each of the test methods in the context of a particular pumping system application.

Constant volume pumping systems have a single possible operating point. Knowledge of the power use at the operating point and the total operating hours are enough to determine annual energy use. The first test method, which evaluates the power use at this single operating point, is naturally suited to this application.

Variable volume pumping systems with constant speed pumps have a single possible operating point for any given flow, as determined by the pump curve at that flow rate. The second and third testing methods were specifically designed for this application. In the second procedure, the power use is measured at one flow rate, and manufacturer's data on the pump, motor, and drive system are used to create a part-load power use curve. The single measured test point is used to calibrate or confirm pump curve reliability. The third testing method does not use pump curve estimations but imposes loads on the system using existing control, discharge, or balancing valves. Since the pump operates at constant speed, it does not matter how the load is imposed. The power use is measured at a range of flow rates to determine the part-load power use curve. In both methods, the part-load power use curve and flow load frequency distribution are used to determine annual energy use.

In variable volume-variable speed pumping applications, the operating point cannot be determined solely from the pump curve and flow load because a given flow could be provided at various pressures or speeds. The system design and control strategy place constraints on either the pressure or flow. A typical variable speed controlled system will have a range of system curves that call for the same flow rate, depending on the occupancy, season, and load. There are two options for accurately determining the part-load power use curve. In both cases, the boundaries of an in-situ test include the pump

TABLE E1-1
Applicability of Test Methods to Common Pumping Systems

Test Method	Pumping System		
	Constant Speed, Constant Volume	**Constant Speed, Variable Volume**	**Variable Speed, Variable Volume**
1. Single point	✓		
2. Single point with manufacturer's pump curve		✓	
3. Multiple point with imposed loads at pump		✓	
4. Multiple point with imposed loads at zone		✓	✓
5. Multiple point through short-term monitoring		✓	✓
6. No-flow test for pump characteristics	✓	✓	✓

TABLE E1-2
Nomenclature for Calculations and Uncertainty Analysis

Value	Symbol	Units/Variable
Bin energy use	E	kWh
Power level	P	kW
Pump capacity / flow rate	Q	gpm, L/s
Total pump pressure	H	ft, psi, kPa
Pump discharge pressure	H_d	ft, psi, kPa
Pump suction pressure	H_s	ft, psi, kPa
Pump rotational speed	S	rpm
Number of hours	T	number
Uncertainty	w	kWh
Total annual uncertainty	U	kWh
Predictor variable	x	varies
Response variable	y	varies
Expected value	E[ ]	x, y
Variance	Var	x^2, y^2
Intercept	β_0	y
1st and 2nd order coefficients	β_1, β_2	y/x, y/x^2
Standard error of regression	σ^2	y^2
Error	ε	x, y
Mean value	μ	x, y
Predicted value symbol	^	NA

and system (piping, valves, and controllers) so that the control strategy is included within the data set. In the fourth method, the power use is measured at a range of loads, which are imposed on the pumping system. The artificial imposition of loads on the system must be done at the zone level in order to account for the control strategy and system design. If loads are imposed directly on the pump, by manipulating control valve position for example, the measurement of power use will not necessarily reflect the building pump and system operating conditions.

For the fifth method, the pump system is monitored as the building experiences a range of thermal loads, with no artificial imposition of loads. An accurate part-load power curve can be developed if the load variation during the monitoring period reflects the full range of annual load characteristics. A representative full-day or half-day monitoring period with natural variations in load may be sufficient. For both methods, the measured part-load power use curves and flow load frequency distribution are used to determine annual energy use. Methods #4 and #5 can also be applied to constant speed, variable flow systems.

The different testing methods have different minimum measurement requirements. In methods where a manufacturer's data or curves are to be used, the minimum measurements include volumetric flow rate, coincident RMS power, differential pressure, and rotational speed. For methods developing a part-load power use curve through direct measurements, only volumetric flow rate and coincident RMS power use are required. Additional measurements may be desired by the user if the data are to be used for more complete analysis and evaluation of the pumping system.

Centrifugal pump performance shall be expressed in the following terms:

a. pump head or pressure difference (ft, psi, kPa)
b. pump capacity, volumetric flow rate (gpm, L/s)
c. pump speed (rpm)
d. pump power (hp, kW)

Centrifugal pump energy characteristics shall be calculated in the following terms:

a. Annual energy use (kWh/yr)
b. Peak energy demand (kW)

Table E1-2 summarizes the symbols used in the testing guidelines for both pump performance calculations and uncertainty analysis.

Pump Data. Prior to the start of testing, record manufacturer, type, size, and serial number of the pump(s), and obtain pump performance curves from the manufacturer. If pump performance curves cannot be obtained, Method #2 may not be used.

Pump and System. Record dimensions and physical condition of the pump. Record dimensions and physical condition of the suction and discharge piping, location of existing pressure taps, and locations and descriptions of piping and/or fittings adjacent to the pump.

Motor Data. Prior to the start of testing, record manufacturer, type, size, and serial number of the motor. Record motor nameplate voltage, amperes, and horsepower or kW.

Motor and Drive. Record dimensions and physical condition of the motor. Record type, dimensions, and physical condition of the drive assembly.

Calibration. Prior to the testing, calibrate all measurement instruments, or provide evidence of current calibration, in accordance with the standards.

Instrumentation. Choose and connect measurement instruments in accordance with the standards.

Operation. Establish and verify prescribed operating conditions and proper operation of pump and test equipment before initiating test.

Precision. Allowable fluctuations in instrumentation must be within the stated limits before recording at required test points.

E1.1 Pump Testing Methods. The test methods detail the measurement requirements for volumetric flow rate, coincident RMS power, differential pressure, and rotational speed at defined operating conditions. Temperature measurements are included to check the consistency of fluid characteristics during the test. Recording of pump and motor nameplate ratings and data are common to all methods. A separate test at shutoff head is required to determine the impeller size if the size cannot be verified through existing documentation.

- **Method #1: Single Point Test**

Description: Measure (i) volumetric flow rate, (ii) coincident RMS power, (iii) differential pressure, and (iv) rotational speed while the pump is at typical operating conditions. Used to confirm design operating conditions and pump and system curves.

Applications: Constant volume, constant speed pumping systems.

Steps:

1. Operate pump at typical existing operating conditions for the system.
2. Measure pump suction and discharge pressure or differential pressure.
3. Measure pump capacity.
4. Measure motor RMS power input.
5. Measure speed.
6. Calculate pump and energy characteristics.

- **Method #2: Single-Point Test with Manufacturer's Pump Curve**

Description: Measure (i) volumetric flow rate, (ii) coincident RMS power, (iii) differential pressure, (iv) rotational speed while the pump is at typical operating conditions. Used with manufacturer's data on the pump, motor, and drive system and engineering principles to determine power at other operating points. Pump operation at other operating conditions is assumed to follow pump curve. If single-point test does not confirm operation within 5% of manufacturer's pump curve, Method #3 or Method #4 must be used.

Applications: Variable volume, constant speed pumping systems

Steps:

1. Obtain manufacturer's pump performance curves. If the performance curves for the pump are not available, Method #2 cannot be used, and Method #3 must be used.
2. Operate pump at typical existing operating conditions.
3. Measure pump suction and discharge pressure or differential pressure.
4. Measure pump capacity.
5. Measure motor RMS power input.
6. Measure speed.
7. Calculate pump and energy characteristics.

- **Method #3: Multiple-Point Test with Imposed Loads at Pump**

Description: Measure (i) volumetric flow rate and (ii) coincident RMS power while the pump is at operated at a range of flow load conditions as prescribed in the test procedures. The loads are imposed downstream of the pump with existing control valves. Pump operation follows the pump curve. Pump differential pressure and rotational speed may also be measured for more complete pump system evaluation.

Applications: Variable volume, constant speed pumping systems

Steps:

1. Operate pump with system configuration set for maximum flow.
2. Measure pump capacity.
3. Measure motor RMS power input.
4. Change system configuration to reduce flow and repeat measurement steps 2 and 3.
5. Calculate pump and energy characteristics.

- **Method #4: Multiple-Point Test with Imposed Loads at Zone**

Description: Monitor (i) volumetric flow rate and (ii) coincident RMS power for a range of building or zone thermal loads as prescribed in the test procedures. The loads are imposed on the building or zones such that the system will experience a broad range of flow rates. The existing pump variable speed control strategy is allowed to operate. Pump differential pressure and rotational speed may also be measured for more complete pump system evaluation.

Applications: Variable volume systems

Steps:

1. Operate pump with system configured for maximum flow rate.
2. Measure pump capacity.
3. Measure motor RMS power input.
4. Change system configuration and repeat measurement steps 2 and 3.
5. Calculate pump and energy characteristics.

- **Method #5: Multiple-Point Test through Short-Term Monitoring**

Description: Monitor i) volumetric flow rate and ii) coincident RMS power for a range of building or zone thermal loads as prescribed in the test procedures. A monitoring period must be selected such that the system will experience a broad range of loads and pump flow rates. Pump differential pressure and rotational speed may also be measured for more complete pump system evaluation.

Applications: Variable volume, variable speed systems

Steps:

1. Choose appropriate time period for test.
2. Monitor pump operation and record data values for pump capacity and motor RMS power input.
3. Calculate pump and energy characteristics.

- **Method #6: No-Flow Test for Pump Characteristics**

Description: Measure (i) differential pressure at zero flow conditions (shut-off head) and compare to manufacturer's pump curves to determine impeller size.

Applications: All types of centrifugal pumps (not recommended for use on positive displacement pumps)

Steps:

1. Run pump at design operating conditions and close discharge valve completely.
2. Measure pump suction and discharge pressure or differential pressure.
3. Measure speed.
4. Calculate shut-off head.
5. Compare shut-off head with manufacturer's pump performance curve to determine and/or verify impeller diameter.

E1.2 Calculations

Flow Load Frequency Distribution. A flow load frequency distribution must be provided by the user of ASHRAE Guideline 14. The distribution must provide the number of operating hours of the system for a set of bins covering the entire range of flow capacity of the system with a maximum normalized range of 10% per bin.

Peak Power Demand. The peak power demand is the maximum instantaneous power use. It is recommended that the recorded peak be measured at an actual operating condition of the pump and system. If the peak demand is not measured during the test and must be calculated from a part-load power curve, it is recommended that the extrapolation from the highest measured power value be no more than 20%. The electric power measurements must be true RMS power, where the instruments measure the active power of the ac circuit, equaling the voltage multiplied by that part of the current in phase with the voltage.

Part-Load Power Curve Calculation. The part-load power use curve is defined as the relationship between pump power and flow rate, and it can be of several functional forms. The choice of the regression model depends on the system type and control strategy (see below). Constant volume, constant speed pumping systems do not require regression analysis because they have a single operating point.

Method #2: Single-Point Test with Manufacturer's Pump Curve. The measurement procedure for Method #2 determines the pump capacity, differential pressure, rotational speed, and power use at a single point. The part-load power curve is determined directly from manufacturer's data. The experimentally measured operating point must correspond to the manufacturer's pump curve within 5% of both capacity and differential pressure in order to continue with Method #2. Equations for the calculation of pump water horsepower, and pump brake horsepower are referenced in ASHRAE Standard 111-1988. The pump affinity laws can be used to make necessary corrections for variations in pump rotational speed. The result of these calculations should be a nearly linear relationship of pump kW as a function of volumetric flow rate.

Methods #3, #4, and #5: Multiple-Point Tests. Variable volume, constant speed pumping systems will generally require the use of a linear regression model with a non-zero intercept. Variable volume, variable speed pumping systems will generally require the use of a second order polynomial regression of power on volumetric flow rate with a non-zero intercept, based on measured power and flow. However, the best model depends on the installation and control strategy. In many cases, the best regression model must be selected from inspection of the experimental data. The uncertainty analysis suggested in clause 6.2 has been explicitly solved for a quadratic regression model.

Annual Energy Use: Normalization. The user may normalize the load and power measurements in order to have the units of part-load ratio and fraction of full-load power. However, the uncertainty analysis is designed for the use of absolute values of measured values and errors. Therefore, the normalization should only be done after all the calculations and uncertainty analysis are complete. The measurements can be normalized to either the maximum measured value or the rated capacity of the equipment.

Annual Energy Use: Constant Volume, Constant Speed Pumping Systems. For a constant volume pumping system, the flow load at the pump is virtually constant. Therefore, the power demand of the pump and motor is nearly constant and the frequency of the load is simply the operating hours of the pump. The total annual energy use is given by Equation E1-1.

$$\underline{E_{annual} = T \cdot P} \tag{E1-1}$$

where

T = annual operating hours

P = equipment power use

Annual Energy Use: Variable Volume Pumping Systems. For both variable volume, constant speed systems and variable volume, variable speed systems, the power demand of the pump and motor varies as a function of the flow requirements of the system. The frequency distribution of the load provides the operating hours of the pump at each bin level, while the in-situ testing determines the part-load power use at each bin level. The total annual energy use is given by Equation E1-2.

$$\underline{E_{annual} = \sum_i (T_i \cdot P_i)} \tag{E1-2}$$

where

i = bin index, as defined by the load frequency distribution

T_i = number of hours in bin i

P_i = equipment power inputat load bin i

E2 Retrofit Isolation Approach for Fans

The test methods detail the measurement requirements for volumetric flow rate, coincident RMS power use, fan differential pressure, and fan rotational speed at defined operating conditions. Temperature and barometer measurements are included to check the consistency of fluid characteristics during the test and to make density corrections if required. Recording of fan and motor nameplate ratings and data are common to all methods.

Fan Data. Prior to the start of testing, record manufacturer, type, size, and serial number of the fan(s), and obtain fan performance curves from the manufacturer. If fan performance curves cannot be obtained, Method #2 may not be used.

Fan and System. Record dimensions and physical condition of the fan and enclosure. Record dimensions and physical condition of the inlet and discharge ductwork, location of existing pressure taps, and locations and descriptions of coils, filters, or other equipment adjacent to the fan.

Motor Data. Prior to the start of testing, record manufacturer, type, size, and serial number of the motor. Record motor nameplate voltage, amperes, and horsepower or kW.

Motor and Drive. Record dimensions and physical condition of the motor. Record type, dimensions, and physical condition of the drive assembly.

Calibration. Prior to the testing, calibrate all measurement instruments, or provide evidence of current calibration, in accordance with the standards.

Instrumentation. Choose and connect measurement instruments in accordance with the standards.

Operation. Establish and verify prescribed operating conditions and proper operation of fan and test equipment before initiating test.

Precision. Allowable fluctuations in instrumentation must be within limits before recording at required test points.

E2.1 Fan Test Methods

- **Method #1: Single-Point Test**

Description: Measure (i) volumetric flow rate, (ii) coincident RMS power use, (iii) fan differential pressure, and (iv) fan rotational speed while the fan is at typical operating conditions. Data are used to confirm design operating conditions and fan and system curves.

Applications: Constant volume fan systems.

Steps:

1. Operate fan at typical existing operating conditions for the system.
2. Measure fan inlet and discharge pressure or (preferably) differential pressure.
3. Measure fan flow capacity.
4. Measure motor RMS power input.
5. Measure fan speed.
6. Calculate fan and energy characteristics.

- **Method #2: Single Point Test with Manufacturer's Data**

Description: Measure (i) volumetric flow rate, (ii) coincident RMS power use, (iii) fan differential pressure, and (iv) fan rotational speed while the fan is at typical operating conditions. Data are used with manufacturer's data on the fan, motor, and drive system and engineering principles to determine power at other operating points. Fan operation at other operating conditions is assumed to follow the fan curve. If single-point test does not confirm operation within 5% of manufacturer's fan curve, Method #3 or Method #4 must be used.

Applications: Variable volume systems without fan control

Steps:

1. Obtain manufacturer's fan performance curves.
2. Operate fan at typical existing operating conditions.
3. Measure fan inlet and discharge pressure, or differential pressure.
4. Measure fan flow capacity.
5. Measure motor RMS power input.
6. Measure fan speed.
7. Calculate fan and energy characteristics.

- **Method #3: Multiple Point Test with Imposed Loads at Fan**

Description: Measure (i) volumetric flow rate and (ii) coincident RMS power while the fan is at operated at a range of flow rate conditions as prescribed in the test procedures. The loads are imposed downstream of the fan with existing dampers. Fan operation follows the fan curve. Fan differential pressure and rotational speed may also be measured for more complete fan system evaluation.

Applications: Variable volume systems without fan control

Steps:

1. Operate fan with system configuration set for maximum flow.
2. Measure fan flow capacity.
3. Measure motor RMS power input.
4. Change system configuration to reduce flow and repeat measurement steps 2 and 3.
5. Calculate fan and energy characteristics.

- **Method #4: Multiple-Point Test with Imposed Loads at Zone**

Description: Measure (i) volumetric flow rate and (ii) coincident RMS power use while the fan is operated at a range of flow rate conditions as prescribed in the test procedures. Thermal loads are imposed at the building or zone level such that the system will experience a broad range of flow rates. The existing fan variable speed control strategy is allowed to operate. Fan differential pressure and rotational speed may also be measured for more complete fan system evaluation.

Applications: Variable volume systems

Steps:

1. Operate fan with system configured for maximum flow rate.
2. Measure fan capacity.
3. Measure motor RMS power input.
4. Change system configuration and repeat measurement steps 2 and 3.
5. Calculate fan and energy characteristics.

- **Method #5: Multiple Point Test through Short Term Monitoring**

Description: Monitor (i) volumetric flow rate and (ii) coincident RMS power while the fan operates at a range of flow rates. The range of flow rates will depend on the building or zones experiencing a wide range of thermal loads. A time period must be selected such that the system will experience a broad range of loads and fan flow rates. The existing fan variable speed control strategy is allowed to operate. Fan differential pressure and rotational speed may also be measured for more complete fan system evaluation.

Applications: Variable volume systems

Steps:

1. Choose appropriate time period for test.
2. Monitor fan operation and record data values for fan capacity and motor RMS power input.
3. Calculate fan and energy characteristics.

E2.2 Calculations

Flow Load Frequency Distribution. A flow load frequency distribution must be provided by the user of ASHRAE Guideline 14. The distribution must provide the number of operating hours of the system for a set of bins covering the entire range of flow capacity of the system with a maximum normalized range of 10% per bin.

Peak Power Demand. The peak power demand is the maximum instantaneous power input. It is recommended that the recorded peak be measured at an actual operating condition of the fan and system. If the peak demand is not measured during the test and must be calculated from a part-load power curve, it is recommended that the extrapolation from the highest measured power value be no more than 20%. The electric power measurements must be true RMS power, where the instruments measure the active power of the ac circuit, equaling the voltage multiplied by that part of the current in phase with the voltage.

Part-Load Power Curve Calculation. The part-load power use curve is defined as the relationship between fan power and volumetric flow rate, and it can be of several functional forms. The choice of the regression model depends on the system type and control strategy (see below). Constant volume, constant speed fan systems do not require regression analysis because they have a single operating point.

Method #2: Single-Point Test with Manufacturer's Fan Curve. The measurement procedure for Method #2 determines the fan capacity, differential pressure, rotational speed, and power use at a single point. The part-load power curve is determined directly from manufacturer's data. The experimentally measured operating point must correspond to the manufacturer's fan curve within 5% of both capacity and differential pressure in order to continue with Method #2. The fan affinity laws, referenced in ASHRAE Standard 111-1988, can be used to make necessary corrections for variations in fan rotational speed, flow rate, or differential pressure. The result of these calculations for constant speed systems should be a nearly linear relationship of fan kW as a function of volumetric flow rate.

Methods #3, #4 and #5: Multiple-Point Tests. Variable volume fan systems without fan control will generally require the use of a linear regression model with a non-zero intercept. Variable volume fan systems with fan control will generally require the use of a second order polynomial regression of power on volumetric flow rate with a non-zero intercept, based on measured power and flow. However, the best model depends on the installation and control strategy. In many cases, the best regression model must be selected from inspection of the experimental data. The uncertainty analysis suggested in clause 6.2 has been explicitly solved for a quadratic regression model.

Annual Energy Use: Normalization. The user may normalize the load and power measurements in order to have the units of part-load ratio and fraction of full-load power. However, the uncertainty analysis is designed for the use of absolute values of measured values and errors. Therefore, the normalization should only be done after all the calculations and uncertainty analysis are complete. The measurements can be normalized to either the maximum measured value or the rated capacity of the equipment.

Annual Energy Use: Constant Volume Fan Systems. For a constant volume system, the flow load at the fan is virtually constant. Therefore, the power demand of the fan and motor is nearly constant and the frequency of the load is simply the operating hours of the fan. The total annual energy use is given by Equation E2-1.

$$\underline{E_{annual} = T \cdot P} \tag{E2-1}$$

where

T = annual operating hours

P = equipment power input

Annual Energy Use: Variable Volume Systems. For variable volume systems with and without fan control, the power demand of the fan and motor varies as a function of the flow requirements of the system. The frequency distribution of the load provides the operating hours of the fan at each bin level, while the in-situ testing determines the part-load power use at each bin level. The total annual energy use is given by Equation E2-2.

$$\underline{E_{annual} = \sum_i (T_i \cdot P_i)} \tag{E2-2}$$

where

i = bin index, as defined by the load frequency distribution

T_i = number of hours in bin i

P_i = equipment power use at load bin I

E3 Retrofit Isolation Approach for Chillers

The chiller testing guidelines provide testing methods to evaluate annual energy use and peak demand characteristics for installed water-cooled chillers. An in-situ testing methodology requires short-term testing procedures to determine the part-load performance of installed chiller systems at a full range of building thermal loads and coincident ambient conditions. The test methods determine chiller power demand at various thermal loads using a thermodynamic model with inputs from direct measurements, statistical regression analysis, manufacturer's data, and engineering principles. The determined part-load power use curve is then used with a load frequency distribution to calculate annual energy use. The user of ASHRAE Guideline 14 has to provide a thermal load frequency distribution, and in some cases coincident chilled water supply and condenser water return temperatures, in order to calculate annual energy use.

A complete performance mapping of chiller operating characteristics would allow for the power use of the chiller to be determined for all operating conditions. However, a complete performance map of chillers is impractical to expect from short-term field measurements. A simpler testing methodology considers the building and the chiller together. If the chiller system is monitored as the building experiences a broad range of thermal loads, the control strategy will be included within the data set. Because of the wide range of chiller systems, control strategies, and climatic zones, no single testing procedure can apply to all system types. The preferred method will be determined by the user based upon the system type and control and the desired level of uncertainty and degree of intrusion.

Chiller systems have two main components, the "load" side, which includes the evaporator characteristics and building load, and the "heat rejection" side, which includes the condenser and the ambient conditions under which it is operating. The "load" side can be controlled to a limited degree in a short-term test by careful timing and manipulation of the building control. The "heat rejection" side can also be controlled to a limited degree by manipulation of cooling tower return water temperature. However, the range of both the load and heat rejection sides of the chiller system will be limited by a bounding set of ambient conditions. Adjustments are required for variable ambient conditions at a range of building thermal loads.

Chiller power use will be a function of:

1. building thermal load
2. evaporator and condenser flow rates
3. entering and leaving chilled water temperatures
4. entering and leaving condenser water temperatures
5. internal chiller controls

Therefore, a large number of independent variables must be considered. Some of these are commonly held constants (e.g., evaporator flow rate) and could be removed from the analysis. Because in-situ performance testing of chillers requires a short-term measurement or monitoring strategy, and power use needs to be evaluated at a wide range of ambient conditions, a model is used to characterize chiller performance from relatively few measurements. A thermodynamically based chiller model that has a limited number of parameters and two levels of complexity make it attractive for practical and effective field testing (Gordon and Ng 1994, 1995). The chiller model has been validated in this project for centrifugal chillers with field data and for reciprocating chillers using manufacturer's data (Gordon and Ng 1994).

One of the testing methods is designed to use manufacturer's data after a single-point performance measurement. Although the thermodynamic model has been validated using manufacturer's data (Gordon and Ng 1994), it is not always possible to do so. Manufacturer's data are based on their own internal models of chiller performance. As such, the accuracy of the data varies with the time of production of the chiller and the degree of complexity of the model used to produce the data. More recently, manufacturers do not publish tables of performance but use computer models designed to size chillers to predict chiller performance at a given set of conditions. Finally, the assumptions of what chiller parameters remain fixed as others change varies among manufacturers. Therefore, the use of chiller performance data for Method #1 may be limited by the chiller's date of production and assumptions of the manufacturer's data.

The following clauses describe the chiller models and the testing methods based on the models.

Chiller performance shall be expressed in the following terms:

a. Evaporator load (tons, kBtu/h, kW)
b. Chilled water supply temperature (°F, °C)
c. Condenser water return temperature (°F, °C)

Chiller energy characteristics shall be calculated in the following terms:

a. Annual energy use (kWh/yr)
b. Peak energy demand (kW)

TABLE E3-1
Nomenclature for Calculations and Uncertainty Analysis

Value	Symbol	Units/ Variable
Bin energy use	E	kWh
Power level	P	kW
Chiller load	Q_{evap}	kBtu, tons, kW
Chilled water supply temperature	T_{chwST}	°F, °C
Condenser water return temperature	T_{chwST}	°F, °C
Number of hours	T	number
Uncertainty	w	kWh
Total annual uncertainty	U	kWh
Predictor variable	x	varies
Response variable	y	varies
Expected value	E[ ]	x, y
Variance	Var	x^2, y^2
Intercept	β_0	y
1st and 2nd order coefficients	β_1, β_2	y/x, y/x^2
Standard error of regression	σ^2	y^2
Error	ε	x, y
Mean value	μ	x, y
Predicted value symbol	^	NA

Table E3-1 summarizes the symbols used in the testing guidelines for the chiller model, chiller performance calculations, and the uncertainty analysis.

Conversion Factors

The following conversion factors can be used to make unit conversions between the various commonly used values for expressing chiller efficiency.

Coefficient of Performance:

$$\text{COP} = \frac{\text{kW refrigeration effect}}{\text{kW input}}$$

Energy Efficiency Ratio:

$$\text{EER} = \frac{\text{Btu/h refrigeration effect}}{\text{watt input}}$$

Power per Ton:

$$\text{kW/ton} = \frac{\text{kW input}}{\text{tons refrigeration effect}}$$

These alternative measures of efficiency are related as follows:

COP = 0.293 EER	EER = 3.413 COP
kW/ton = 12/EER	EER = 12/(kW/ton)
kW/ton = 3.516 COP	COP = 3.516/(kW/ton)

Chiller Data. Prior to the start of testing, record manufacturer, type, size, and serial number of the chiller, and obtain chiller performance data from the manufacturer. The use of chiller performance data for Method #1 may be limited by the chiller's date of production and assumptions of manufacturer's data (see Clause 3.1 for a discussion on the use of manufacturer's data).

Chiller and System. Evaluate and record the physical condition of the chiller. Record dimensions and physical condition of the evaporator and condenser piping, location of existing instrumentation, and locations and descriptions of pumps or other equipment adjacent to the chiller.

Calibration. Prior to the testing, calibrate all measurement instruments, or provide evidence of current calibration, in accordance with Annex A2.

Instrumentation. Choose and connect measurement instruments in accordance with clauses 6 and 7 and Annexes A and B and all requirements of the instrumentation manufacturers.

Operation. Establish and verify prescribed operating conditions and proper operation of chiller and test equipment before initiating test.

E3.1 Thermodynamic Chiller Model Description. The chiller model expresses chiller efficiency as 1/COP because it has a linear relationship with 1/(evaporator load). The final result of the model can then be inverted to the conventional efficiency measures of COP or kW per ton.

E3.2 Simple Model. The simpler version of the chiller model developed by Gordon and Ng (1994) predicts a linear relationship between 1/COP and $1/Q_{evap}$, with a scatter about the line due to variations in evaporator and condenser water temperatures. Coefficients found by using the performance data in linear regressions characterize the irreversibilities of the particular chiller in question. Once the coefficients have been determined, the simple model will predict chiller COP as a function of evaporator load. Equation E3-2 shows all the terms of the simpler form of the model. In the resulting prediction Equation E3-3, the coefficient c_1 characterizes the internal chiller losses, while the coefficient c_0 combines the other terms of the simple model.

$$\frac{1}{COP} = -1 + (T_{cwRT}/T_{chwST}) + \left(\frac{1}{Q_{evap}}\right)\left(\frac{q_{evap}T_{cwRT}}{T_{chwST}} - q_{cond}\right) + f_{HX} \tag{E3-2}$$

$$\frac{1}{COP} = c_1\left(\frac{1}{Q_{evap}}\right) + c_0 \tag{E3-3}$$

where

T_{cwRT}	=	entering (return) condenser water temperature (K)
T_{chwST}	=	leaving (supply) evaporator water temperature (K)
Q_{evap}	=	evaporator load
q_{evap}	=	rate of internal losses in evaporator
q_{cond}	=	rate of internal losses in condenser
f_{HX}	=	dimensionless term (normally negligible, see Gordon et al. 1995)
c_1 & c_0	=	linear regression coefficients

The simple model requires measurement of the chiller load (evaporator flow rate, entering and leaving chilled water temperatures) and coincident RMS power use only. Variations in chilled water supply and condenser water return temperatures are not considered. The simple model is applicable to chiller systems with constant temperature control of evaporator and condenser temperatures, chiller systems whose control and climate limit the variation of evaporator and condenser temperatures, and chiller systems where evaporator and condenser temperatures are a function of chiller load.

E3.3 Temperature-Dependent Model. The temperature-dependent model carries the thermodynamic analysis one step further by defining the losses in the heat exchangers of the evaporator and condenser as a function of the chilled water supply and condenser water return temperatures. The resulting expression has three coefficients (A_0, A_1, A_2) that replace the terms for the internal losses (q_{evap}, q_{cond}) in the simple chiller model. The simple model is a special limiting case of the temperature-dependent model. The result is in an expression for chiller 1/COP as a function of the evaporator load, chilled water supply temperature, and condenser water return temperature. These parameters are commonly reported in manufacturer's performance data and are also commonly controlled chiller plant variables. The coefficients (A_0, A_1, A_2) found by using the performance data in linear regressions characterize the irreversibilities of the particular chiller in question. Once the coefficients have been determined, the temperature-dependent model predicts chiller COP under a wide range of operating conditions. Equation E3-4 shows the form of the temperature-dependent model.

$$\frac{1}{COP} = -1 + (T_{cwRT}/T_{chwST}) + \frac{-A_0 + A_1(T_{cwRT}) - A_2(T_{cwRT}/T_{chwST})}{Q_{evap}} \tag{E3-4}$$

The temperature-dependent model requires measurement of the chiller load (evaporator flow rate, entering and leaving chilled water temperatures), coincident RMS power use, chilled water supply temperature, and condenser water return temperature. Variations in chilled water supply and condenser water return temperatures are considered in the model. The temperature-dependent model is applicable to all chiller systems.

Temperature-Dependent Model Implementation Procedure:

To implement the temperature-dependent model, measured data of chiller load, coincident RMS power use, chilled water supply temperature, and condenser water return temperature are used to calculate the three coefficients (A_0, A_1, A_2). A plot of α (Equation E3-5) versus the temperature ratio (T_{cwRT}/T_{chwST}, kelvin) should result in a set of parallel straight lines, one for each value of condenser water return temperature. The slope of the regression lines determines the value of coefficient A2.

$$\alpha = \left(\frac{1}{COP} + 1 - (T_{cwRT}/T_{chwST})\right)Q_{evap} \tag{E3-5}$$

A plot of β (Equation E3-6), using the value of A_2 already calculated, versus the condenser water return temperature (T_{cwRT}, Kelvin) should result in a single straight line. The slope of the regression line determines the value of coefficient A_1 while the intercept determines the value of coefficient A_0.

$$\beta = \frac{\left(\frac{1}{COP} + 1 - (T_{cwRT}/T_{chwST})\right)Q_{evap} + A_2(T_{cwRT}/T_{chwST})}{} \tag{E3-6}$$

After calculation of the model coefficients, Equation E3-4 is used to predict the COP for a wide range of measured input parameters of chiller load, chilled water supply temperature, and condenser water return temperature.

E3.4 Chiller Testing Methods. Five testing methods have been developed. In all cases, the data are used to implement either the simple or temperature-dependent model described in the previous clauses. For those methods using the simple model, the load profile will be limited to an evaporator load frequency distribution. For those methods using the temperature-dependent model, the load profile will include coincident chilled water supply and condenser water return temperatures in addition to the evaporator load frequency distribution.

- **Method #1 - Single Point Test with Manufacturer's Data**

Description: A single operating point test requiring measurement of (i) RMS power input, (ii) evaporator flow rate, (iii) entering and (vi) leaving chilled water temperatures, and (v) return condenser water temperature while the chiller system operates at existing typical conditions. Used to confirm design operating conditions and manufacturer's data at a single point and determine the validity of model predictions based on manufacturer's data.

Applications: All chiller systems with available data

Steps:

1. Obtain manufacturer's chiller performance data. If the performance curves for the chiller are not available, Method #1 is not applicable. The data must be analyzed to determine if it is applicable to the thermodynamic model.
2. Operate chiller at typical existing operating conditions.
3. Measure evaporator load.
4. Measure coincident chilled water supply temperature.
5. Measure coincident condenser water return temperature.
6. Measure coincident chiller RMS power input.
7. Calculate chiller and energy characteristics.

- **Method #2 - Imposed Load Test for Simple Model**

Description: A multiple operating point test requiring measurement of (i) RMS power input, (ii) evaporator flow rate, (iii) entering, and (iv) leaving chilled water temperatures while the chiller system operates at a range of thermal load conditions. The load variations are imposed on the building through manipulation of cooling setpoints or internal gains to obtain a range of loads typical of annual operation for the system. The simple thermodynamic model is then used to develop a linear regression fit of COP as a function of load. Variations in chilled water supply and condenser water return temperatures are not considered.

Applications: (i) Chiller systems with constant temperature control of evaporator and condenser temperatures; (ii) Chiller systems whose control and climate limit the variation of evaporator and condenser temperatures; (iii) Chiller systems where evaporator and condenser temperatures are a function of chiller load.

Steps:

1. Operate chiller at typical existing operating conditions.
2. Measure evaporator load..
3. Measure coincident chiller RMS power input.
4. Change building cooling setpoints to increase or decrease evaporator load and repeat measurement steps 2 and 3.
5. Calculate chiller and energy characteristics.

- **Method #3 - Imposed Load Test for Temperature Dependent Model**

Description: A multiple operating point test requiring measurement of (i) RMS power input, (ii) evaporator flow rate, (iii) entering and (iv) leaving chilled water temperatures, and (v) return condenser water temperature while the chiller system operates at a range of thermal load conditions. The load variations are imposed on the building through manipulation of cooling setpoints or internal gains, while coincident variations in chilled water and condenser water temperatures are also imposed to obtain a range of operating conditions typical of annual operation for the system. The temperature-dependent thermodynamic model is then used to determine the coefficients of the model to calculate COP as a function of load, chilled water supply temperature, and condenser water return temperature.

Applications: All chiller systems

Steps:

1. Operate chiller at typical existing operating conditions.
2. Measure evaporator load.
3. Measure coincident chilled water supply temperature.
4. Measure coincident condenser water return temperature.
5. Measure coincident chiller RMS power input.
6. Change building cooling setpoints or internal gains to increase or decrease evaporator load and repeat measurement steps 2, 3, 4, and 5.
7. Calculate chiller and energy characteristics.

- **Method #4 - Short-Term Monitoring Test for Simple Model**

Description: A short-term monitoring test requiring measurement of (i) RMS power input, (ii) evaporator flow rate, (iii) entering, and (iv) leaving chilled water temperatures while the chiller system operates at a range of thermal load conditions. A time period for the test is selected such that the load variations are representative of annual operation for the system. The simple thermodynamic model is then used to develop a linear regression fit of COP as a function of load. Variations in chilled water supply and condenser water return temperatures are not considered.

Applications: (i) Chiller systems with constant temperature control of evaporator and condenser temperatures; (ii) chiller systems whose control and climate limit the variation of evaporator and condenser temperatures; (iii) chiller systems where evaporator and condenser temperatures are a function of chiller load.

Steps:

1. Choose appropriate time period for test.
2. Monitor chiller operation and record data values for evaporator load and coincident chiller RMS power input.
3. Calculate chiller and energy characteristics.

- **Method #5 - Short-Term Monitoring Test for Temperature-Dependent Model**

Description: A short-term monitoring point test requiring measurement of (i) RMS power input, (ii) evaporator flow rate, (iii) entering and (iv) leaving chilled water temperatures, and (v) return condenser water temperature while the chiller system operates at a range of thermal load conditions. A time period for the test is selected such that the load and water temperature variations are representative of annual operation for the system. The temperature-dependent thermodynamic model is then used to determine the coefficients of the model to calculate COP as a function of load, chilled water supply temperature, and condenser water return temperature.

Applications: All chiller systems

Steps:

1. Choose appropriate time period for test.
2. Monitor chiller operation and record data values for evaporator load, coincident chilled water supply temperature, coincident condenser water return temperature, and coincident chiller RMS power input.
3. Calculate chiller and energy characteristics.

E3.5 Calculations

Load Frequency Distribution. A load frequency distribution must be provided by the user of ASHRAE Guideline 14. The simple model requires a chiller load distribution only. The distribution must provide the number of operating hours of the system for a set of bins covering the entire range of chiller loads with a maximum normalized range of 10% per bin. The temperature-dependent model requires a chiller load distribution with coincident chilled water supply temperature and condenser water return temperature. The size of the coincident temperature bins can greatly affect the total number of bins. It is recommended that 1°F or 2°F temperature bins be used with the temperature-dependent model calculations.

Peak Power Demand. The peak power demand is the maximum instantaneous power use. It is recommended that the recorded peak be measured at an actual operating condition of the chiller and system. If the peak demand is not measured during the test and must be calculated from a part-load power curve, it is recommended that the extrapolation from the highest measured power value be no more than 20%. The electric power measurements must be true RMS power, where the instruments measure the active power of the ac circuit, equaling the voltage multiplied by that part of the current in phase with the voltage.

Part-Load Power Curve Calculation. The part-load power use curve will be determined by the choice of chiller model. See E3.2 for the implementation procedures for the simple and temperature-dependent chiller models. For the temperature-dependent chiller model, the chilled water supply temperature and condenser water return temperature must be in degrees Kelvin for the regression calculations.

Method #1: Single-Point Test with Manufacturer's Data. The chiller manufacturer's data should be used to develop the simple or temperature-dependent model coefficients before testing. If the data are consistent with the model, the measurement procedure for Method #1 determines the chiller capacity, power input, chilled water supply temperature, and condenser water return temperature at a single point. The part-load power curve is determined directly from manufacturer's data. The experimentally measured operating point must correspond to the manufacturer's chiller data within 5% of both capacity and power use in order to continue with Method #1. The model coefficients from the chiller manufacturer's data can then be used to determine the power use of the chiller at a range of loads and water temperatures.

Annual Energy Use. For calculation of annual energy use, the simple or temperature-dependent models determine the power demand of the chiller at each bin of the load distribution. The load frequency distribution and the two water temperatures, provides the operating hours of the chiller at each bin level. The energy use for each bin is given by Equation E3-7. The power level for each bin is given by Equation E3-8. The total annual energy use is given by Equation E3-9.

$$E_i = T_i \cdot P_i \tag{E3-7}$$

$$P_i = (1/Eff_i) \cdot (Q_{evap,\,i}) \tag{E3-8}$$

$$E_{annual} = \sum_i (T_i \cdot P_i) \tag{E3-9}$$

where

i	=	bin index, as defined by load frequency distribution
T_i	=	number of hours in bin i
P_i	=	equipment power use at load bin i
Eff_i	=	chiller 1/COP in bin i
$Q_{evap,i}$	=	chiller load in bin i

Annual Energy Use: Normalization. The user may normalize the load and power measurements in order to have the units of part-load ratio and fraction of full-load power. However, the uncertainty analysis is designed for the use of absolute values of measured values and errors. Therefore, the normalization should only be done after all the calculations and uncertainty analysis are complete. The measurements can be normalized to either the maximum measured value or the rated capacity of the equipment.

E3.6 References

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E4 Retrofit Isolation Approach for Boilers and Furnaces

- **Method #1a: Single-Point Test (Direct Method)**

Description: Measure (i) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.) (ii) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), (iii) heat inputs.

Applications: Non-reheat boilers and furnaces.

Steps:

Operate boiler at typical existing operating conditions for the system.

Measure mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.).

Measure mass flow and enthalpy of fluid streams entering the boiler (feedwater desuperheating sprays, etc.).

Measure heat inputs.

Calculate efficiency using the direct efficiency method.

Calculate boiler and efficiency characteristics.

- **Method #1b: Single-Point Test (Direct Heat Loss Method)**

Description: Measure (i) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss and unaccounted for losses) (ii) heat inputs.

Applications: Non-reheat boilers and furnaces.

Steps:

1. Operate boiler at typical existing operating conditions for the system.
2. Measure all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses).
3. Measure heat inputs.
4. Calculate efficiency using direct heat loss method.
5. Calculate boiler and efficiency characteristics.

- **Method #1c: Single-Point Test (Indirect Combustion Method)**

Description: Measure: (i) enthalpy of all combustion products, (ii) enthalpy of fuel, (iii) enthalpy of combustion air, (iv) heat inputs.

Applications: Non-reheat boilers and furnaces.

Steps:

1. Operate boiler at typical existing operating conditions for the system.
2. Measure enthalpy of all combustion products, the enthalpy of the fuel, the enthalpy of combustion air.
3. Measure heat inputs.
4. Calculate efficiency using the indirect combustion method.
5. Calculate boiler and efficiency characteristics.

- **Method #2a: Single-Point Test with Manufacturer's Data (Direct Method)**

Description: Measure (i) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.) (ii) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), (iii) heat inputs. Data are used with manufacturer's published boiler efficiency curves and engineering principles to determine efficiency at other operating points. Boiler efficiency at other operating points is assumed to follow the manufacturer's curve. If single point does not confirm manufacturer's curve within 5%, another boiler efficiency method will need to be used.

Applications: Non-reheat boilers and furnaces.

Steps:

1. Operate boiler at typical existing operating conditions for the system.
2. Obtain manufacturer's boiler efficiency curve.
3. Measure mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.).
4. Measure mass flow and enthalpy of fluid streams entering the boiler (feedwater desuperheating sprays, etc.).
5. Measure heat inputs.
6. Calculate efficiency using the direct efficiency method for the single point and compare to manufacturer's curve.
7. Calculate boiler and efficiency characteristics.

- **Method #2b: Single Point Test with Manufacturer's Data (Direct Heat Loss Method)**

Description: Measure (i) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss and unaccounted for losses) (ii) heat inputs. Data are used with manufacturer's published boiler efficiency curves and engineering principles to determine efficiency at other operating points. Boiler efficiency at other operating points is assumed to follow the manufacturer's curve. If single point does not confirm manufacturer's curve within 5%, another boiler efficiency method will need to be used.

Applications: Non-reheat boilers and furnaces.

Steps:

1. Operate boiler at typical existing operating conditions for the system.
2. Obtain manufacturer's boiler efficiency curve.
3. Measure all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses).
4. Measure heat inputs.
5. Calculate efficiency using direct heat loss method for a single point and compare to manufacturer's curve.
6. Calculate boiler and efficiency characteristics.

- **Method #2c: Single-Point Test with Manufacturer's Data (Indirect Combustion Method)**

Description: Measure (i) enthalpy of all combustion products, (ii) enthalpy of fuel, (iii) enthalpy of combustion air, (iv) heat inputs. Data are used with manufacturer's published boiler efficiency curves and engineering principles to determine efficiency at other operating points. Boiler efficiency at other operating points is assumed to follow the manufacturer's curve. If single point does not confirm manufacturer's curve within 5%, another boiler efficiency method will need to be used.

Applications: Non-reheat boilers and furnaces.

Steps:

1. Operate boiler at typical existing operating conditions for system.
2. Obtain manufacturer's boiler efficiency curve.
3. Measure enthalpy of all combustion products, the enthalpy of the fuel, and the enthalpy of combustion air.
4. Measure heat inputs.
5. Calculate efficiency using the indirect combustion method and compare to manufacturer's curve.
6. Calculate boiler and efficiency characteristics.

- **Method #3a: Multiple-Point Test with Imposed Loads (Direct Method)**

Description: Measure over a range of operating conditions (i) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.) (ii) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), (iii) heat inputs. Different loads are imposed on the boiler and measurements repeated. Boiler operation is assumed to follow manufacturer's efficiency curve.

Applications: Non-reheat boilers and furnaces.

Steps:

1. Obtain manufacturer's efficiency curves.
2. Operate boiler at a given load.
3. Measure mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.).
4. Measure mass flow and enthalpy of fluid streams entering the boiler (feedwater desuperheating sprays, etc.).
5. Measure heat inputs.
6. Calculate efficiency using the direct efficiency method.
7. Change load on boiler and repeat steps 2 through 6.
8. Calculate boiler and efficiency characteristics.

- **Method #3b: Multiple-Point Test with Imposed Loads (Direct Heat Loss Method)**

Description: Measure over a range of operating conditions (i) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss and unaccounted for losses) and (ii) heat inputs. Different loads are imposed on the boiler and measurements repeated. Boiler operation is assumed to follow manufacturer's efficiency curve.

Applications: Non-reheat boilers and furnaces.

Steps:

1. Obtain manufacturer's boiler efficiency curve.
2. Operate boiler at a given load.
3. Measure all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses).
4. Measure heat inputs.
5. Calculate efficiency using direct heat loss method for a single point and compare to manufacturer's curve.
6. Change load on boiler and repeat steps 2 through 5.
7. Calculate boiler and efficiency characteristics.

- **Method #3c: Multiple-Point Test with Imposed Loads (Indirect Combustion Method)**

Description: Measure over a range of operating conditions (i) enthalpy of all combustion products, (ii) enthalpy of fuel, (iii) enthalpy of combustion air, (iv) heat inputs. Different loads are imposed on the boiler and measurements are repeated. Boiler operation is assumed to follow the manufacturer's efficiency curve.

Applications: Non-reheat boilers and furnaces.

Steps:

1. Obtain manufacturer's boiler efficiency curve.
2. Operate boiler at a given load.
3. Measure enthalpy of all combustion products, the enthalpy of the fuel, and the enthalpy of combustion air.
4. Measure heat inputs.
5. Calculate efficiency using the indirect combustion method and compare to manufacturer's curve.
6. Change load on boiler and repeat steps 2 through 5.
7. Calculate boiler and efficiency characteristics.

- **Method #4a: Multiple Point Test through Short Term Monitoring (Direct Method)**

Description: Monitor over a range of operating conditions (i) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.) (ii) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), (iii) heat inputs. The range of boiler loads should cover the normally expected loads that the boiler will experience (low and high).

Applications: Non-reheat boilers and furnaces.

Steps:

1. Choose appropriate time period for test.
2. Monitor boiler operation and record data values for mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.), mass flow and enthalpy of fluid streams entering the boiler (feedwater desuperheating sprays, etc.), and heat inputs.
3. Calculate efficiency using the direct efficiency method.
4. Calculate boiler and efficiency characteristics.

- **Method #4b: Multiple-Point Test through Short-Term Monitoring (Direct Heat Loss Method)**

  Description: Monitor over a range of operating conditions: (i) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses)and (ii) heat inputs. The range of boiler loads should cover the normally expected loads that the boiler will experience (low and high).

  Applications: Non-reheat boilers and furnaces.

  Steps:

1. Choose appropriate period for the test.
2. Monitor all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses), and monitor heat inputs.
3. Calculate efficiency using direct heat loss method for a single point and compare to manufacturer's curve.
4. Calculate boiler and efficiency characteristics.

- **Method #4c: Multiple-Point Test through Short-Term Monitoring (Indirect Combustion Efficiency Method)**

  Description: Monitor over a range of operating conditions (i) enthalpy of all combustion products, (ii) enthalpy of fuel, (iii) enthalpy of combustion air, and (iv) heat inputs. The range of boiler loads should cover the normally expected loads that the boiler will experience (low and high).

  Applications: Non-reheat boilers and furnaces.

  Steps:

1. Choose appropriate time period for test.
2. Monitor enthalpy of all combustion products, the enthalpy of the fuel, the enthalpy of combustion air, and monitor heat inputs.
3. Calculate efficiency using the indirect combustion method and compare to manufacturer's curve.
4. Calculate boiler and efficiency characteristics.

E4.2 Calculations.

Flow Load Frequency Distribution. A boiler load frequency distribution must be provided by the user of ASHRAE Guideline 14. The distribution must provide the number of operating hours of the system for a set of bins covering the entire range of flow capacity of the system with a maximum normalized range of 10% per bin.

Peak Power Demand (Electric Boilers). The peak power demand is the maximum instantaneous power use. It is recommended that the recorded peak be measured at an actual operating condition of the boiler. If the peak demand is not measured during the test and must be calculated from a part-load power curve, it is recommended that the extrapolation from the highest measured power value be no more than 20%. The electric power measurements must be true RMS power, where the instruments measure the active power of the ac circuit, equaling the voltage multiplied by that part of the current in phase with the voltage.

Part-Load Boiler Curve Calculation. The part-load boiler use curve is boiler efficiency (y-axis) plotted against the boiler capacity (x-axis), with the maximum value on the x-axis representing the maximum boiler capacity. The choice of the regression model depends on the system type and control strategy.

Method #2: Single-Point Test with Manufacturer's Fan Curve. The measurement procedure for Method #2 determines the boiler efficiency at a given capacity. The part-load power curve is determined directly from manufacturer's data. The experimentally measured operating point must correspond to the manufacturer's curve within 5% of both capacity and efficiency in order to continue with Method #2.

Methods #3, and #4: Multiple-Point Tests. Boilers with variable fire rates will generally require the use of a linear regression model with a non-zero intercept. The best model depends on the installation and control strategy. In many cases, the best regression model must be selected from inspection of the experimental data.

Annual Energy Use: Constant Fire Boilers. For constant fire boilers, the boiler load is virtually constant. Therefore, the fuel input is nearly constant and the frequency of the load is simply the operating hours of the boiler. The total annual energy use is given by:

$$E_{annual} = T \cdot P \qquad \text{(E4-1)}$$

where

T = annual operating hours

P = equipment power use

Annual Energy Use: Variable Fire Boilers. For variable fire boilers, the output of the boiler varies as does the fuel input. The frequency distribution of the load provides the operating hours of the boiler at each bin level, while the in-situ testing determines the part-load fuel input and boiler efficiency at each bin level. The total annual energy use is given by:

$$E_{annual} = \sum_i (T_i \cdot P_i) \qquad \text{(E4-2)}$$

where

i = bin index, as defined by load variable frequency distribution

T_i = number of hours in bin i

P_i = equipment fuel input (and efficiency) at load bin (i)

E5 Retrofit Isolation Approach for Lighting

E5.1 Thermal interaction and lighting usage profiles

Thermal Interactions. Lighting retrofits can decrease cooling loads and increase heating loads by an amount equal to the thermal load of the wattage reduction caused by the lighting retrofit. The amount of the cooling reduction or heating increase will vary depending upon the type of HVAC system, chiller and boiler efficiency, and cost of cooling or heating fuel. Previously published studies show the cooling interaction can increase savings by 10% to 20%. The increased heating requirements can reduce savings by 5% to 20% (Bou Saada et al.1996).

Lighting Usage Profiles. The calculation of savings from lighting retrofits involves ascertaining the wattage reduction associated with the new fixtures and an estimate or measurement of the hours per day that the lights are used. Lighting usage profiles can be sampled with lighting loggers or measured at the electrical distribution panel. Lighting usage profiles can be predictable (e.g., weekday, weekend vary by less than 10%) or variable.

Predictable lighting usage profile. Typical of office buildings where the lighting profile is predictable for weekday and weekend diversity profiles. Sampling of profiles will probably predict diversity profiles (e.g., ±10%).

Variable lighting usage profile. Typical of buildings with variable occupancy such as conference centers and/or hotels/motels. Sampling of profiles will not predict diversity profiles (e.g., ≥ 10%).

Lighting Levels. Lighting levels should be sampled before and after the retrofit. All lighting retrofits should use IES recommended lighting levels (or better). Any pre-retrofit condition that is not maintaining IES lighting levels should be documented and brought to the attention of the building owner or administrator. Adjustments may need to be made if post-retrofit lighting levels are greater that pre-retrofit lighting levels.

Daylighting. Lighting retrofits can involve the installation of daylighting sensors to dim fixtures near the perimeter of the building or below skylights when IES recommended lighting levels can be maintained with daylighting and/or supplemental lighting. Measuring the savings from such retrofits usually involves before-after measurements of electrical power and lighting usage profiles.

E5.2 Methods for calculating savings from lighting measurements

1. Baseline and post-retrofit measured lighting power levels and stipulated diversity profiles.
2. Baseline and post-retrofit measured lighting power levels and sampled baseline and post-retrofit diversity profiles.
3. Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit power levels with post-retrofit continuous diversity profile measurements.
4. Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit continuous submetered lighting.
5. Method #1, #2, or #3 with measured thermal effect (heating and cooling).
6. Baseline and post-retrofit submetered lighting measurements and thermal measurements.

- **Method #1: Before/after measured lighting power levels and stipulated diversity profiles**

Description: (i) Obtain before-after lighting power levels using RMS watt/fixture measurements for the pre-retrofit fixtures and the post-retrofit fixtures, (ii) stipulate the lighting usage profiles using the best available information that represents lighting usage profiles for the facility.

Application:

- Exterior lighting on a timer or photocell.
- Interior hallway lighting or any interior lighting used continuously or on a timer.

Steps:

1. Obtain measured RMS watt/fixture data for pre-retrofit and post-retrofit fixtures.
2. Count the fixtures associated with each functional area in the building (e.g., areas that have different usage profiles).
3. Define the lighting usage profiles for each functional area using the appropriate information that represents lighting

TABLE E-4
Lighting Methods

Type Of Measurement	Lighting Power Levels	Lighting Diversity Factors	Thermal Interaction
1. Baseline and post-retrofit measured lighting power levels and stipulated diversity profiles.	Sampled before and after	Stipulated	No thermal interaction
2. Before/after measured lighting power levels with sampled before/after diversity profiles.	Sampled before and after	Sampled before and after	No thermal interaction
3. Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit power levels with continuous diversity profile measurements.	Sampled before and after	Sampled before and continuously measured after	No Thermal Interaction
4. Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit continuous submetered lighting.	Sampled before and continuously measured after	Sampled before. Continuous submetering used after	No Thermal Interaction
5. #1, #2, or #3 with stipulated thermal effect.	Uses #1, #2, or #3	Uses #1, #2 or #3	Calculated Thermal Interaction
6. Before/after submetered lighting and thermal measurements.	Measured before and after	Measured before and after	Measured Thermal Interactions.

usage profiles (e.g., continuously on, on during evening hours, etc.).

4. Calculate lighting energy usage characteristics.

- **Method #2: Baseline and post-retrofit measured lighting power levels and sampled baseline and post-retrofit diversity profiles**

Description: (i) Measure lighting power levels using RMS watt meter for a sample of the pre-retrofit fixtures and the post-retrofit fixtures; (ii) measure the lighting usage profiles using light loggers or portable metering attached to the lighting circuits.

Application:

- Any exterior lighting or interior lighting with predictable usage profiles.

Steps:

1. Measure watt/fixture using RMS watt meter for pre-retrofit and post-retrofit fixtures.
2. Count the fixtures associated with each functional area in the building (i.e., areas that have different usage profiles).
3. Sample lighting usage profiles for each functional area using lighting loggers and/or portable submetered RMS watt meters on lighting circuits.
4. Calculate lighting energy usage characteristics.

- **Method #3: Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit measured power levels with post-retrofit continuous diversity profile measurements**

Description: (i) Obtain lighting power levels using RMS watt/fixture measurements for the pre-retrofit fixtures and the post-retrofit fixtures; (ii) sample the baseline lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits; (iii) continuously measure the post-retrofit lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits.

Application:

- Any exterior lighting or interior lighting.

Steps:

1. Obtain lighting power levels using RMS watt/fixture measurements for the pre-retrofit fixtures and the post-retrofit fixtures.
2. Sample the baseline lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits.
3. Continuously measure the post-retrofit lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits.
4. Calculate lighting energy usage characteristics.

- **Method #4: Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit continuous submetered lighting**

Description: (i) Obtain lighting power levels using RMS watt/fixture measurements for the pre-retrofit fixtures; (ii) sample the baseline lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits; (iii) continuously measure the post-retrofit lighting power usage using RMS watt measurements on submetered lighting circuits.

Application:

- Any exterior lighting or interior lighting.

Steps:

1. Obtain lighting power levels using RMS watt/fixture measurements for the pre-retrofit fixtures.
2. Sample the baseline lighting usage profiles using light loggers or RMS watt measurements on submetered lighting circuits.
3. Continuously measure the post-retrofit lighting usage using RMS watt measurements on submetered lighting circuits.
4. Calculate lighting energy usage characteristics.

- **Method #5: Uses Method #1, #2 or #3 with calculated thermal effect (Heating and Cooling)**

Description: (i) Obtain lighting power profiles and usage using Method(s) #1, #2, #3, or #4; (ii) calculate the heating or cooling system efficiency using HVAC component isolation methods described in this document; (iii) calculate decrease in cooling load and increase in heating load.

Application:

- Any interior lighting.

Steps:

1. Obtain lighting power profiles and usage using Method(s) #1, #2, or #3,
2. Calculate the heating or cooling system efficiency using HVAC component isolation methods described in this document,
3. Calculate lighting energy usage characteristics.
4. Calculate decrease in cooling load and increase in heating load.

- **Method #6: Baseline and post-retrofit sub-metered lighting measurements and thermal measurements**

Description: (i) Obtain lighting energy usage by measuring RMS lighting use continuously at the submetered level for pre-retrofit and post-retrofit conditions; (ii) obtain thermal energy use data by measuring submetered cooling or heating energy use for pre-retrofit and post-retrofit conditions; (iii) develop representative lighting usage profiles from the submetered lighting data.

Application:

- Any interior lighting projects.
- Any exterior lighting projects (no thermal interaction).

Steps:

1. Obtain measured submetered lighting data for pre-retrofit and post-retrofit periods.

2. Develop representative lighting usage profiles from the submetered lighting data.
3. Calculate lighting energy usage characteristics.
4. Calculate decrease in cooling load and increase in heating load.

E5.3 Calculations.

Annual Energy Use. Annual energy use is calculated according to the methods described in Table E-5. The savings are then determined by comparing the annual lighting energy use during the baseline period to the annual lighting energy use during the post-retrofit period.

The thermal energy effect can either be calculated using the component efficiency methods or it can be measured using whole-building, before-after cooling and heating measurements.

Peak Power Demand. The peak power demand is the maximum instantaneous power use determined by an evaluation of the 24-hour profiles for the baseline and post-retrofit period.

Reductions in peak power demand can then be calculated by comparing peak electricity use for similar days (e.g., same month, same day of the week, according to demand billing period).

If the peak demand is not measured during the test and must be calculated from a part-load power curve, it is recommended that the extrapolation from the highest measured power value be no more than 20%. The electric power measurements must be true RMS power, where the instruments measure the active power of the ac circuit, equaling the voltage multiplied by that part of the current in phase with the voltage.

If peak reductions from the chiller are being considered, then it is recommended that component efficiency tests of the chiller be performed to correspond to the increased/decreased load on the chiller.

E5.4 References

Bou Saada, T., J. Haberl, J. Vajda, and L. Harris. 1996. Total Utility Savings From the 37,000 Fixture Lighting Retrofit to the USDOE Forrestal Building. *Proceedings of the 1996 ACEEE Summery Study.*

E6 Retrofit Isolation Approach for Unitary and Split Condensing Equipment

E6.1 Statement of the Problem. The need for a retrofit isolation measurement and verification plan and test procedure for unitary and split-condensing equipment is driven by the extraordinary prevalence of such equipment in the residential, commercial, and industrial building population. As clause 5.4 states, a good savings measurement plan should "address the balance between the level of uncertainty and the costs of the process." This properly recognizes that if a monitoring protocol costs more to implement than the energy saved by the new piece of equipment, it is of little value. When dealing with unitary and split condensing equipment, the levels of uncertainty are higher and costs of the equipment are lower than virtually all other pieces of HVAC equipment for which other measurement of energy and demand savings protocols have been developed elsewhere in this guideline. Indeed, many pieces of smaller unitary and condensing equipment may either cost as little as $1,000 or use as little as $500 or less in annual energy costs, which is the installed cost of a few monitoring points. Thus, a unitary and condensing equipment protocol is going to have to use a minimum number of monitoring points and include more simplifying assumptions and have more uncertainty than the protocols for other bigger, more complicated pieces of HVAC equipment found elsewhere in this guideline to maintain this necessary balance between uncertainty and cost.

Furthermore, these simplifying assumptions will tend to almost always understate the actual energy and demand savings delivered by the new equipment. The benefits to building owners in the form of rebates and quantifying even at the low end through the development of an energy and demand savings measurement protocol for unitary and split condensing equipment outweigh their shortcomings.

While the measurement of baseline data for the equipment to be replaced would tend to result in higher quality data, this involves monitoring the equipment for a fairly significant period of time before the old equipment can be replaced. Thus, such methods impose a significant cost to the building owner in the form of lost energy savings for the period of time where the equipment could have been replaced and was not because historical submetering data were being collected. It is assumed in the development of this protocol that the building owner is going to want to maximize the energy and demand savings by replacing the equipment as soon as possible. The cost issue also exerts a disproportionately bigger effect in a pre-construction measurement/post-construction measurement protocol compared to other larger pieces of HVAC equipment where this lost energy savings penalty is proportionately smaller.

It should be kept in mind that most unitary and split condensing equipment tends to operate by cycling compressors, condenser fans, and/or burners on and off in response to variations in load. This is in contrast to larger, more expensive, and more complicated pieces of HVAC equipment, such as centrifugal chillers, which respond to load variations by non-linear methods, such as variable speed drives, hot gas bypass, and inlet guide vanes. The on-off control of most unitary and split condensing equipment provides a convenient starting point for the simplifying assumption of linearity in comparing the operation of the old vs. the new equipment. Of course, the performance of unitary and split system air-cooled compressors does vary slightly in response to the condensing temperatures of the equipment but much less so than, say, a water-cooled centrifugal chiller. Lower condensing temperatures do result in an increase in compressor efficiency.

E6.2 Factors Affecting Unitary and Split Condenser Performance. The actual performance between old and new unitary and split condenser equipment in buildings can vary widely due to the following factors among others:

1. adequacy of duct sealing
2. proper refrigerant charge and air flow

TABLE E-5
Calculations

Type of Measurement	Pre-Retrofit Electricity Usage Calculations	Post-Retrofit Electricity Usage Calculations	Thermal Energy Usage Calculations
1. Baseline and post-retrofit measured lighting power levels and stipulated diversity profiles.	For each lighting circuit: Annual energy use = (Power levels) × (24-hr stipulated profiles) × (number of days assigned to each profile)	For each lighting circuit: Annual energy use = (Power levels) × (24-hr stipulated profiles) × (number of days assigned to each profile)	None.
2. Before/after measured lighting power levels with sampled before/after diversity profiles.	For each lighting circuit: Annual energy use = (Power levels) × (24-hr sampled profiles) × (number of days assigned to each profile)	For each lighting circuit: Annual energy use = (Power levels) × (24-hr sampled profiles) × (number of days assigned to each profile)	None.
3. Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit power levels with continuous diversity profile measurements.	For each lighting circuit: Annual energy use = (Power levels) × (24-hr sampled profiles) × (number of days assigned to each profile)	For each lighting circuit: Annual energy use = (Power levels) × (continuous diversity profile measurements)	None.
4. Baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit continuous submetered lighting.	For each lighting circuit: Annual energy use = (Power levels) × (24-hr sampled profiles) × (number of days assigned to each profile)	For each lighting circuit:Annual use = submetered lighting energy use.	None.
5. #1, #2, #3, or #4 with calculated thermal effect.	Annual use = method #1, #2, #3, or #4 as appropriate.	Annual use = method #1, #2, #3, or #4 as appropriate.	Pre- and post-thermal load from the lighting is calculated using the component efficiency measurement methods for HVAC systems.
6. Before/after submetered lighting and thermal measurements.	For each lighting circuit:Annual use = submetered lighting energy use.		Pre- and post-thermal load is calculated using before-after whole-building cooling and heating submetered measurements.

3. corrosion and fouling of heat transfer surfaces (old equipment)
4. adequacy of fan static pressure
5. adequacy or presence (or lack thereof) of economizer cycle operation
6. adequacy of condenser fan control and operation
7. proper matching of compressor and thermostat stages
8. proper matching of condensing unit and evaporator in split systems
9. adequacy of thermostat location
10. proper or improper system balancing
11. adequacy of refrigerant piping seals and valves
12. adequacy of compressor motor and refrigerant seals
13. adequacy of system capacity to system requirements
14. type of HVAC system being used (e.g., constant volume, VAV, multi-zone, reheat, etc.)

Because of the difficulty quantifying these and other factors a simplified M&V plan for unitary and split condensing equipment could have significant uncertainty.

E6.3 Method for Split Condensing Equipment (Cooling Only)

a. *Measurement approach*

A split condensing (cooling only) unit can be considered and modeled as a combination of the following elements:

- a constant speed air-conditioning compressor(s) that cycles on/off in response to load variations
- a constant speed air-conditioning condenser fan(s) that cycle(s) on/off in response to load variation

The proposed measurement approach relies on making the simplifying assumption of constant efficiency about each of these two elements. A relatively small subset of available unitary equipment may have two-speed compressors that may complicate the use of this method.

1. Measurement approach for constant speed compressor(s):

The new compressor will be continuously monitored for power consumption over each month by a power meter wired to a current transformer connected to the power input for the entire compressor motor circuit.

2. Measurement approach for a constant speed condenser fan(s):

The new condenser section will be continuously monitored for power consumption over each month by a power meter wired to a current transformer connected to the power input for entire the condenser fan motor circuit.

b. *Baseline period data*

If baseline period data are available from the above, mentioned equipment, it can be used to calibrate the performance of the old unit that is to be removed and demonstrate how much less efficient than nameplate efficiency it operates at to determine the actual SSEER.

c. *Algorithm for savings determination*

The determination of energy and demand savings for the newly installed unitary equipment is the sum of the following two elements:

- compressor demand and energy savings
- condenser fan demand and energy savings

1. Energy savings for constant speed compressor(s):

Energy savings per period = (New Compressor Measured kWh/period) × [1-(Old eqpt. nameplate SEER)/(New eqpt. nameplate SEER)] × [products of applicable adjustment factors in clause 6]

2. Energy savings for constant speed condenser fan(s):

Energy savings per period = (New Condenser Fan(s) Measured kWh/period) × [1-(Old eqpt. nameplate condenser fan watts/(New eqpt. nameplate condenser fan watts)] × [products of applicable adjustment factors in clause 6]

d. *The measurement procedure*

The energy use of the new compressor(s) and condenser(s) will be monitored and summed over the period of time of interest (usually monthly) by an electronic data logger or energy management system.

e. *Quality control procedures*

The primary equipment types used for this method are electric power meters wired to current transformers. The polarity of the current transformers (CTs) should be verified to be correct upon their installation. Shunt resistors and CT output should be verified upon installation.

f. *Savings reporting frequency and format*

The usual reporting frequency for the energy savings is monthly or as required by the owner or terms of the performance contract. The format will consist of the following information in column format:

Eqpt. ID:

Compressor/Condenser

Kwh/period:

Old nameplate SEER:

New nameplate SEER:

Adjustment Factors:

Energy Savings:

Numerical data in all columns to be summed up.

E6.4 Method for Split Heat Pump Condensing Equipment

a. *Measurement approach*

A split heat pump condensing unit can be considered and modeled as a combination of the following elements:

- a constant speed air-conditioning compressor(s) that cycles on/off in response to load variations
- a constant speed air-conditioning condenser fan(s) that cycle(s) on/off in response to load variation
- a constant speed heat pump compressor(s) that cycles on/off in response to load variations
- an electric resistance heater below certain outdoor air temperature, say 30°F

The proposed measurement approach relies on making the simplifying assumption of constant efficiency about each of these elements.

1. Measurement approach for constant speed compressor(s):

The new compressor will be continuously monitored for power consumption over each month by a power meter wired to a current transformer connected to the power input for the entire compressor motor circuit. A sensor will indicate whether or not the compressor is acting in cooling or heating mode. Energy use by the compressor will be totaled separately to indicate the total energy use in cooling mode and in heating mode during each monitoring period.

2. Measurement approach for a constant speed condenser fan(s):

The new condenser section will be continuously monitored for power consumption over each month by a power meter wired to a current transformer connected to the power input for entire the condenser fan motor circuit.

3. Measurement approach for supplemental electric resistance heat:

Unless it can be shown otherwise, it will be assumed that any electric resistance heat usage at very low outdoor ambient conditions is a wash between the old equipment and the new equipment.

b. *Baseline period data*

If baseline period data are available from the abovementioned equipment, it can be used to calibrate the performance of the old unit that is to be removed and demonstrate how much less efficient than nameplate efficiency it operates at to determine the actual SEER.

c. *Algorithm for savings determination*

The determination of energy and demand savings for the newly installed unitary equipment is the sum of the following elements:

- compressor cooling demand and energy savings
- compressor heating demand and energy savings
- condenser fan demand and energy savings

1. Cooling energy savings for constant speed compressor(s):

Energy savings per period = (New Compressor Measured kWh/period) × [1-(Old eqpt. nameplate SEER)/(New eqpt. nameplate SEER)] × [products of applicable adjustment factors in clause 6]

2. Heating energy savings for constant speed compressor(s):

Energy savings per period = (New Compressor Measured kWh/period) × [1-(Old eqpt. nameplate heat pump SEER)/(New eqpt. nameplate heat pump SEER)] × [products of applicable adjustment factors in clause 6]

3. Energy savings for constant speed condenser fan(s):

Energy savings per period = (New Condenser Fan(s) Measured kWh/period) × [1-(Old eqpt. nameplate condenser fan watts/(New eqpt. nameplate condenser fan watts)] × [products of applicable adjustment factors in clause 6]

d. *The measurement procedure*

The energy use of the new compressor(s) and condenser(s) will be monitored and summed over the period of time of interest (usually monthly) by an electronic data logger or energy management system.

e. *Quality control procedures*

The primary equipment types used for this method are electric power meters wired to current transformers. The polarity of the current transformers (CTs) should be verified to be correct upon their installation. Shunt resistors and CT output should be verified upon installation.

f. *Savings reporting frequency and format*

The usual reporting frequency for the energy savings is monthly or as required by the owner or terms of the performance contract. The format will consist of the following information in column format:

Eqpt. ID:
Compressor/Condenser
Kwhr/period cooling:
Kwhr/period heating:
Old nameplate SEER:
New nameplate SEER:
Old nameplate HP heating efficiency:
New nameplate HP heating efficiency:
Adjustment Factors:
Energy Savings:
Numerical data in all columns to be summed up.

E6.5 Method for Unitary Equipment

a. *Selected measurement approach and compliance path*

A piece of unitary HVAC equipment can be considered and modeled as a combination of the following elements:

- a constant speed compressor(s) that cycles on/off in response to load variations
- a constant speed condenser fan(s) that cycle(s) on/off in response to load variation
- a constant speed ventilation fan
- a heater section that cycles on/off in response to load variation

The proposed measurement approach relies on measuring or making assumptions about each of these four elements. A relatively small subset of available unitary equipment may have variable or two-speed compressors or ventilation fans that may complicate the use of this method.

1. Measurement approach for constant speed compressor(s):

The new compressor will be continuously monitored for power consumption over each month by a power meter connected to current transformer connected to the power input for the entire compressor motor circuit.

2. Measurement approach for a constant speed condenser fan(s):

The new condenser section will be continuously monitored for power consumption over each month by a power meter connected to current transformer connected to the power input for entire the condenser fan motor circuit.

3. Measurement approach for a constant speed ventilation fan:

The new ventilator fan will be continuously monitored for power consumption over each month by a power meter connected to current transformer connected to the power input for ventilator fan motor circuit.

4. Measurement approach for heater section:

If the new heater section is natural gas-fired, a gas meter will be inserted in the natural gas pipe leading to the furnace section to measure monthly natural gas consumption. If the new heater section is supplied with hot water or steam, then a Btu meter will be inserted to measure the thermal input to the unit. If the old and new heater sections are electric resistance, this can be dispensed with since there will be no significant energy savings.

b. *Baseline period data*

If baseline period data that include performance at ARI conditions are available from the above-mentioned equipment, it can be used to calibrate the performance of the old unit that is to be removed and demonstrate how much less efficient than nameplate efficiency it operates.

c. *The algorithm for savings determination*

The determination of energy and demand savings for the newly installed unitary equipment is the sum of the following four elements:

- compressor demand and energy savings
- condenser fan demand and energy savings
- evaporator fan demand and energy savings
- heater section energy savings

1. Energy savings for constant speed compressor(s):

Energy savings per period = (New Compressor Measured kWh/period) × [1-(Old eqpt. nameplate SEER)/(New eqpt. nameplate SEER)] × [products of applicable adjustment factors in clause 6]

2. Energy savings for constant speed condenser fan(s):

Energy savings per period = (New Condenser Fan(s) Measured kWh/period) × [1-(Old eqpt. nameplate condenser fan watts/(New eqpt. nameplate condenser fan watts)] × [products of applicable adjustment factors in clause 6]

3. Energy savings for ventilation fan section:

Energy savings per period (kWh) = (New Ventilation Fan(s) Measured kWh/period) × [1-(Old eqpt. nameplate ventilation fan watts/(New eqpt. nameplate ventilation fan watts)] × [products of applicable adjustment factors in clause 6]

4. Electric savings for natural gas heating section:

Electric savings per period (kWh) = (# ft^3 of natural gas used per period) × (Btu per cu. Ft. of gas) × (combustion efficiency of unit) × (1 kWh/3,413 Btu)

5. Electric demand savings:

Demand savings per period = [(Old eqpt. nameplate SEER) × (Old eqpt. nameplate capacity (tons))] - [(New eqpt. nameplate SEER) × (New eqpt. nameplate SEER)]

d. *The measurement procedure*

The energy use of the new compressor(s) and condenser(s) will be monitored and summed over the period of time of interest (usually monthly) by an electronic data logger or energy management system.

e. *Quality control procedures*

The primary equipment types used for this method are electric power meters wired to current transformers. The polarity of the current transformers (CTs) should be verified to be correct upon their installation. Shunt resistors and CT output should be verified upon installation.

f. *Savings reporting frequency and format*

The usual reporting frequency for the energy savings is monthly, or as required by the owner or terms of the performance contract. The format will consist of the following information in column format:

Eqpt. ID:

Compressor/condenser/ventilator fan:

Cooling kWhr/period:

Ventilation fan kWhr/period:

Old nameplate SEER:

New nameplate SEER:

Natural gas or thermal heat/period:

Avoided electric heat energy in kWh/period:

Adjustment factors:

Energy savings:

Numerical data in all columns to be summed up.

E6.6 Ancillary System Improvement Adjustment Factors

Very often the new equipment installed will either have features not found in the old equipment removed (e.g., airside economizer cycle) or will be accompanied by other ancillary measures whose energy savings may not be realized by the previous protocols. The following system improvement factors are intended to address that gap.

a. *Installation of airside economizer in new equipment when old equipment did not have it*

Many older rooftop unitary HVAC units may not have airside economizer "free cooling cycle" capability or controls, or if they do, the controls may have failed. The following prescriptive methods can allow for an adjustment factor to make up for the extra energy savings from the new airside economizer cycle that are not picked up by the basic energy savings protocol.

1. Computer simulation:

The additional cooling savings from the installation of the airside economizer cycle may be calculated prescriptively by a computer energy simulation program comparing the old equipment operation without the economizer to the new equipment operation with the economizer cycle.

2. Bin or modified bin method:

The additional cooling savings from the installation of the airside economizer cycle may be calculated prescriptively by employing a bin method or modified bin method to determine the fraction of annual cooling energy saved by the installation of an economizer cycle.

3. Default value method:

In the E-Cube study, the savings from an airside economizer were computer simulated for a 10-ton rooftop unit located in Boston, Mass. The result was a 32% cooling energy savings. Based on this, a default value of 30% is recommended if site-specific computer simulations or bin method analysis is possible.

E6.7 References

ASHRAE 1999 HVAC Applications Handbook

ASHRAE 2001 Fundamentals Handbook

E-Cube, Inc., Transforming Northeast Markets to Increase Energy Efficiency, Jan. 23, 1998.

Pacific Gas & Electric Company, Rooftop Unit Performance Analysis Tool - A Case Study, Dec. 31, 1998.

E7 Retrofit Isolation Generic Test Procedure

This generic test procedure is provided as a template for future applications not currently detailed in Annex E. Example text and editorial comment are shown in italic.

1. PURPOSE

This procedure prescribes a uniform set of testing methods for determining the energy and demand savings of a specific equipment item or subsystem *(be specific, e.g., cool storage system)*.

2. SCOPE

2.1 This test procedure includes the following:

a. definitions and terminology
b. a general description of test method(s) provided
c. required information and conditions for initiating a test
d. a uniform method of testing
e. identification of test equipment and measurement points for performing such tests
f. applications where use of a specific method is appropriate
g. identification of data required for analysis and calculations to be used

2.2 *If necessary, include items that are not included or covered by this procedure.*

3. DEFINITIONS

This clause would include definitions for any new terms or for definitions of existing terms that are being applied under a new context.

4. CLASSIFICATIONS

This clause would name and briefly describe the various test methods that may be employed.

Tests performed under this test method are classified as follows:

4.1 *Example: Cool Storage System Efficiency Test measures the cycle specific energy use of the system.*

5. REQUIREMENTS

5.1 Initialization. *List requirements that must be met prior to initiating the test, e.g., cool storage systems tested under this procedure shall be fully operational with all components, including all control components and control sequences, installed and working.*

5.2 Required information. *List any special requirements that must obtained or defined by the individual performing the test prior to conducting the test. Examples include the following:*

The following information shall be specified by the individual performing the test prior to performing tests under this procedure:

a Design specifications, performance curves, sequence of operations, operating conditions to be evaluated.

b. A specified load profile against which the system is to be tested. The load profile shall include flow rates and supply and return temperatures for each portion of the system under test, and the corresponding expected state of charge of the thermal storage device, for each hour of the storage cycle.

c. Maximum and minimum allowable ambient temperatures during the test interval.

6. TEST METHODS

6.1 Method 1

6.1.1 Description. *Describe method, including any general test condition requirements that must be adhered to.*

6.1.2 Applications. *Provide examples for which this method could be applied.*

6.1.3 Test Configuration and Data to be Recorded.

6.1.3.1 *Label (e.g., T1) and name (e.g., fluid temperature leaving the cool storage system under test) each measurement point for each test identified in clause 4. It is recommended that a schematic (Figure 1) be provided of the specific equipment item or subsystem, which includes the measurement location of each point.*

6.1.3.2 *List any special requirements of the test configuration such as test duration, number of readings, and interval between readings.*

6.1.4 Test Conditions. *List any specific requirements for a particular method that must be adhered to.*

6.1.5 Instruments

6.1.5.1 General. Instruments, whether existing or installed specifically for the purpose of testing, shall meet the requirements of 6.1.5. *Specific requirements should be provided in this clause if a particular method is especially dependent upon sensor characteristics or measurement approach.*

6.1.5.2 Measurement Type. *List each measurement type, any measurement standard if applicable, accuracy, precision, and resolution requirements and any special instructions, such as it is recommended that the same instrumentation be used for pre- and post-retrofit testing. An example is as follows:*

6.1.5.2.1 ***Temperature***

a. Temperature shall be measured in accordance with ASHRAE Standard 41.1-1986 (RA 91).

b. The rated accuracy, precision, and resolution of the instruments and their associated readout devices shall be within the following limits:

	Temperature	*Temperature Difference*
Accuracy	*±0.15°C (±0.3°F)*	*±0.10°C (±0.2°F)*
Precision	*±0.10°C (±0.2°F)*	*±0.075°C (±0.15°F)*
Resolution	*±0.05°C (±0.1°F)*	*±0.05°C (±0.1°F)*

c. The installed accuracy of temperature sensors shall be verified as specified in 6.1.5.4.

d. Temperature sensors used for measuring the temperature difference across a component should be calibrated as matched pairs by the manufacturer and then verified in the field.

6.1.5.3 Data Recording Instruments. *List any specific data recording instrument requirements.*

6.1.5.4 Field Calibration and Verification of Test Instruments. *List any specific field verification of test instruments requirements. An example is as follows:*

6.1.5.4.1 *The installed accuracy of measurement instruments shall be verified to be within the limits specified in 6.1.5.2.*

6.1.5.4.2 *Field verification of installed accuracy shall be completed no more than three months prior to the date of the test.*

6.1.5.4.3 *Instruments used to verify the accuracy of field-installed instruments shall have been calibrated no more than one year prior to the date of the test.*

6.1.5.4.4 *Post test calibration shall be performed on the following instruments: ....*

6.1.6 Steps

6.1.6.1 Initialization. Before any testing is performed, the equipment or subsystem under test shall have been initialized as specified in 5.1.

6.1.6.2 *Provide a detailed list of steps of how the test is to be conducted. Note that method must adhere to the requirements of Guideline 14, 6.2 Retrofit Isolation Approach.*

7. CALCULATION OF RESULTS

7.1 Nomenclature, Symbols, and Subscripts. *List and define nomenclature, symbols, and subscripts (use 2001 ASHRAE Handbook—Fundamentals, Chapter 36); include units of measure and provide detail as appropriate.*

7.2 Calculation Method. *Provide detailed calculation methodology including the equations used. Note that method must adhere to the requirements of Guideline 14, 6.2 retrofit isolation approach.*

8. TEST REPORT

List the requirements of the test report, which are provided in Guideline 14, 5.3.2.3 Retrofit Isolation Performance Path, as applicable.

9. REFERENCES

List references cited in this procedure.

POLICY STATEMENT DEFINING ASHRAE'S CONCERN FOR THE ENVIRONMENTAL IMPACT OF ITS ACTIVITIES

ASHRAE is concerned with the impact of its members' activities on both the indoor and outdoor environment. ASHRAE's members will strive to minimize any possible deleterious effect on the indoor and outdoor environment of the systems and components in their responsibility while maximizing the beneficial effects these systems provide, consistent with accepted standards and the practical state of the art.

ASHRAE's short-range goal is to ensure that the systems and components within its scope do not impact the indoor and outdoor environment to a greater extent than specified by the standards and guidelines as established by itself and other responsible bodies.

As an ongoing goal, ASHRAE will, through its Standards Committee and extensive technical committee structure, continue to generate up-to-date standards and guidelines where appropriate and adopt, recommend, and promote those new and revised standards developed by other responsible organizations.

Through its *Handbook*, appropriate chapters will contain up-to-date standards and design considerations as the material is systematically revised.

ASHRAE will take the lead with respect to dissemination of environmental information of its primary interest and will seek out and disseminate information from other responsible organizations that is pertinent, as guides to updating standards and guidelines.

The effects of the design and selection of equipment and systems will be considered within the scope of the system's intended use and expected misuse. The disposal of hazardous materials, if any, will also be considered.

ASHRAE's primary concern for environmental impact will be at the site where equipment within ASHRAE's scope operates. However, energy source selection and the possible environmental impact due to the energy source and energy transportation will be considered where possible. Recommendations concerning energy source selection should be made by its members.